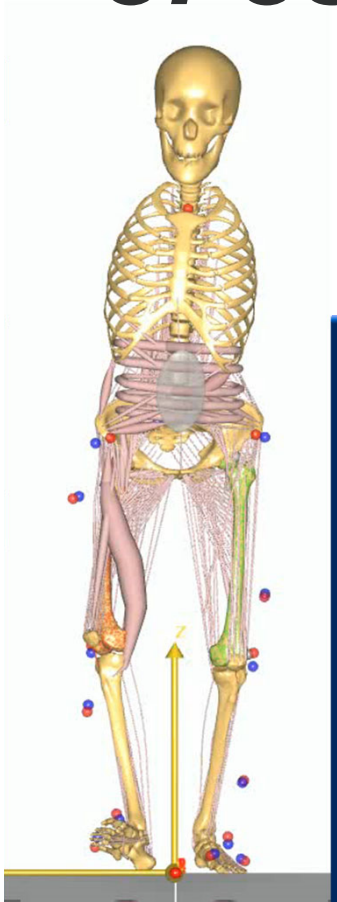
A novel workflow using AnyBody Modeling System and Mechanical Finder to do finite element analysis of osteoarthritic gait



04/12/2018

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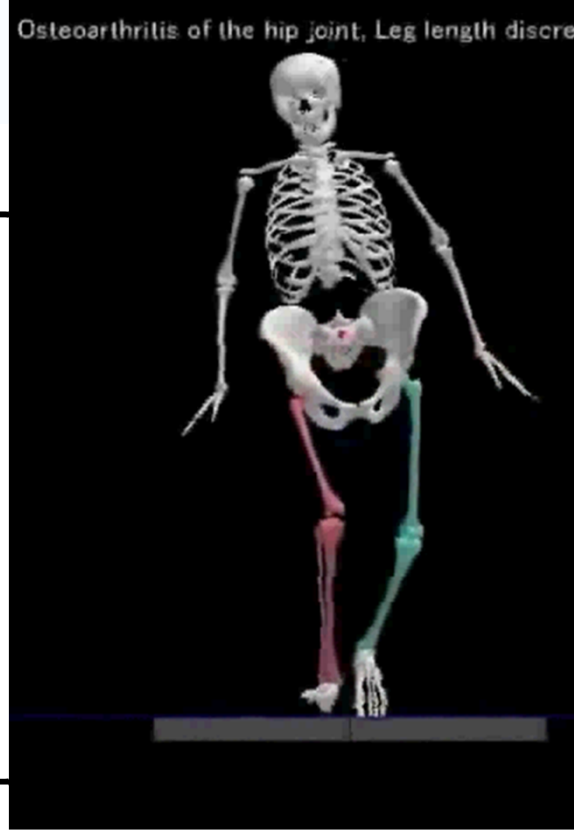
Ryukoku University, Japan

Introduction

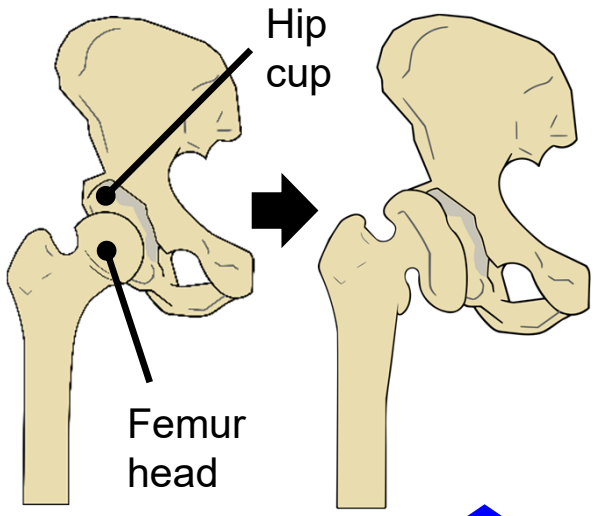
http://www.youtube.com/watch?v=NkbJjaKW07k



Hip osteoarthritis

- Deforms the femur and hip cup due to friction of articular cartilage

➡ Abnormal gait due to a decrease of muscle forces and leg length inequality



Total Hip Arthroplasty (THA)

Closely related to *)

Forces occurring in muscles/bones in gait motion

(*) T.C. Doehring, et al., Journal of Arthroplasty, (1996).

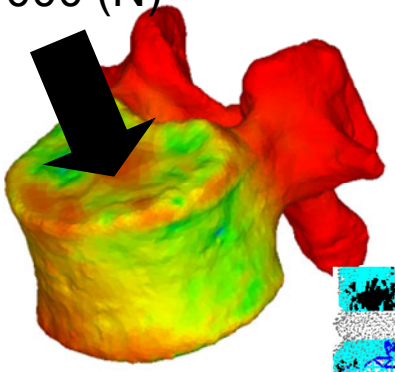
To assess/predict …

- Relationship between the seriousness and abnormal gait
- Recovery of gait motion after THA
- Determination of THA position
- Bone remodeling around an implant …

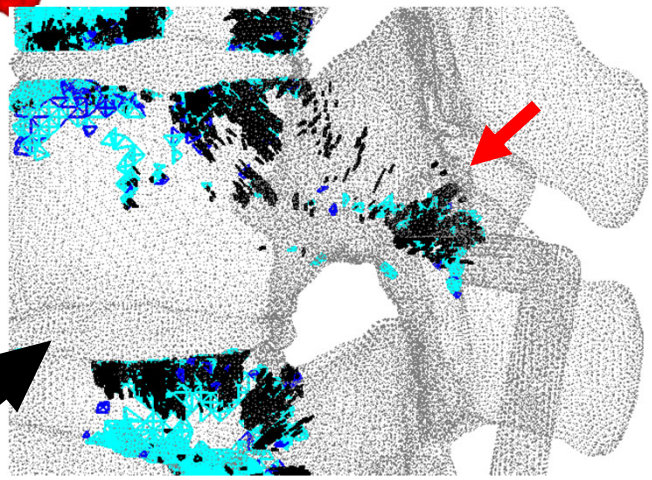
➡ Subject-specific (stress) analysis is necessary.

Introduction

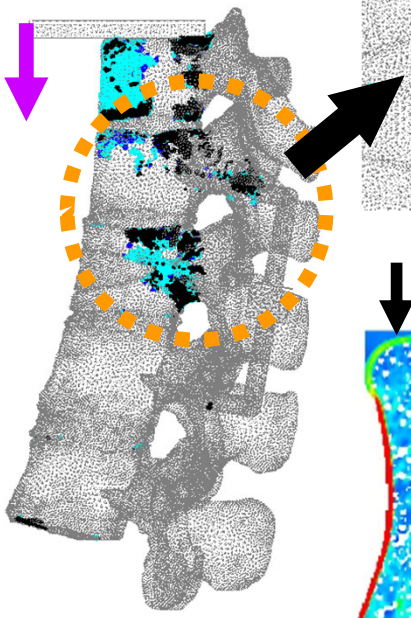
1000 (N)

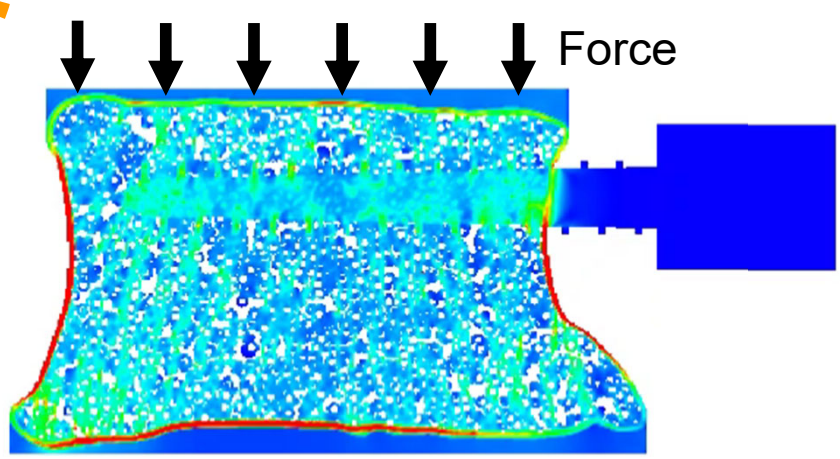


Finite element (FE) model

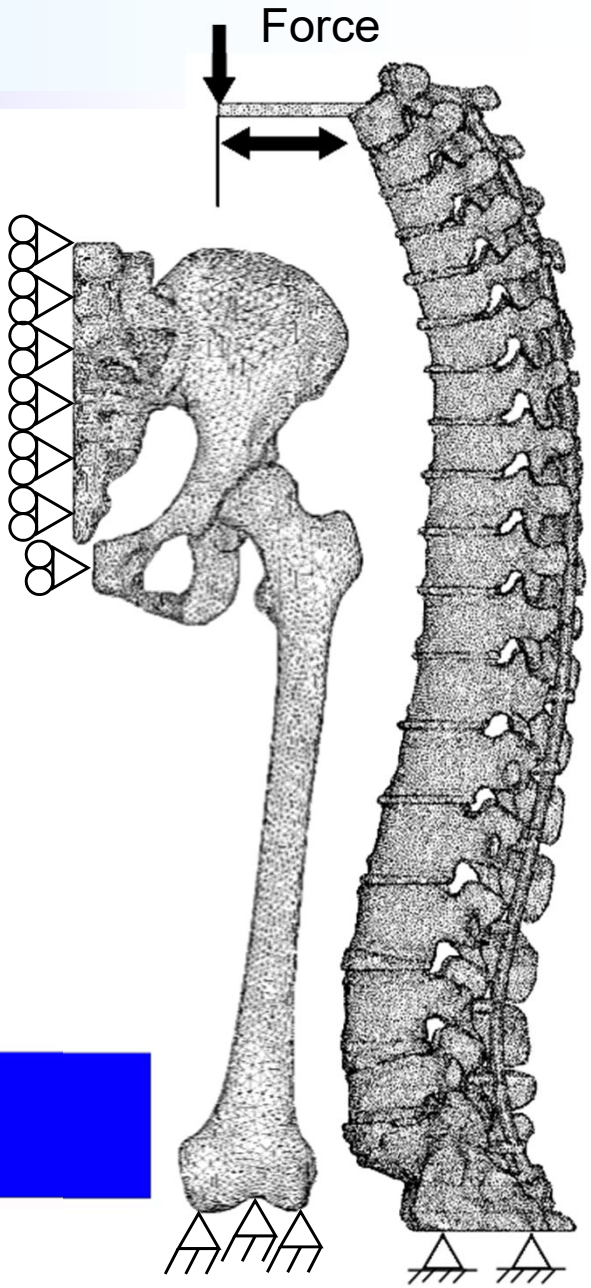


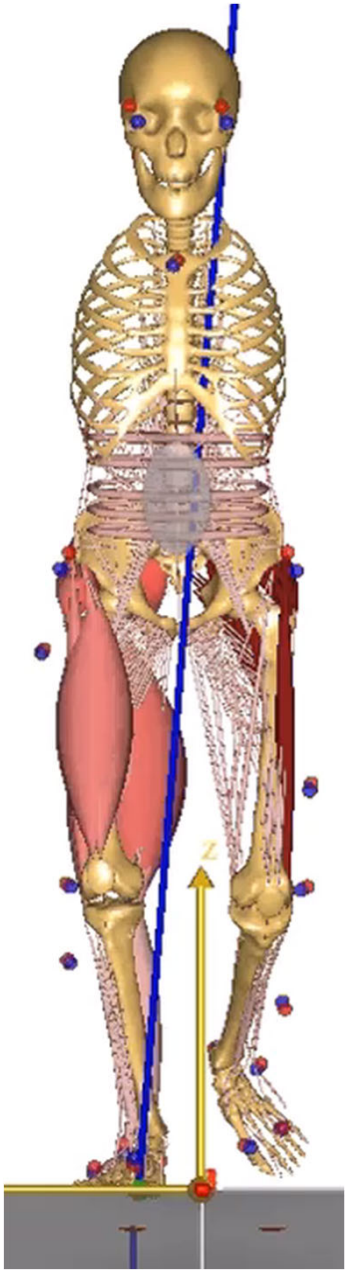
Force





Force





- Boundary conditions (BCs) are simple !

Musculoskeletal simulation (AnyBody: AMS)

Aims

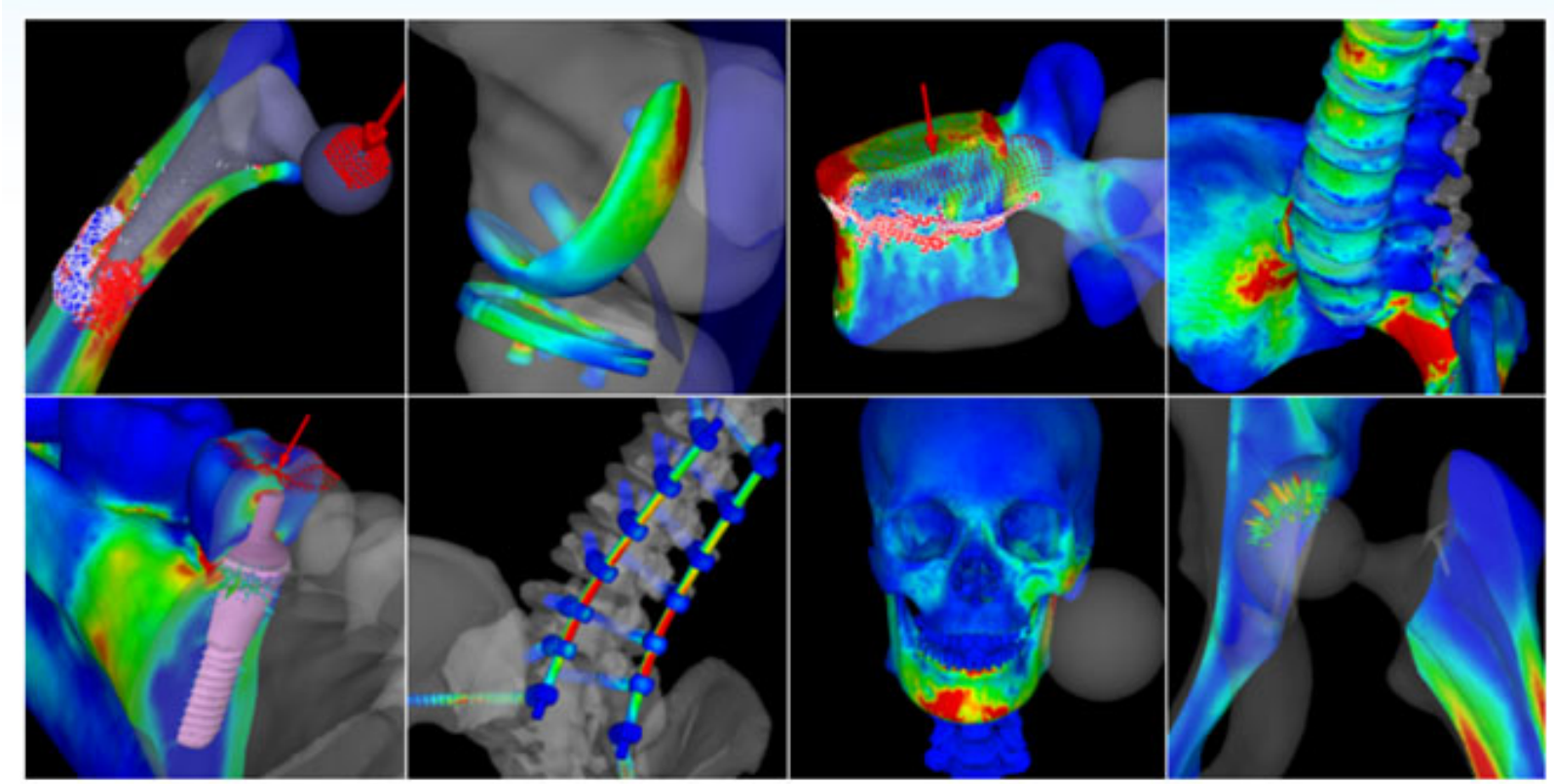
- To construct a computational flow of FEA using AMS and finite element system (Mechanical Finder: MF).
- Development of the subject-specific musculoskeletal model for gait motion of osteoarthritis patients.
- To assess gait restoration after surgery and detect important muscles to improve abnormal gait treatment strategy.

FEA system of bone - Mechanical Finder (RCCM Co., Ltd., Japan) -

MECHANICAL FINDER (MF)

Japanese

- A software for CT image-based modeling and FEA of bone.



RCCM

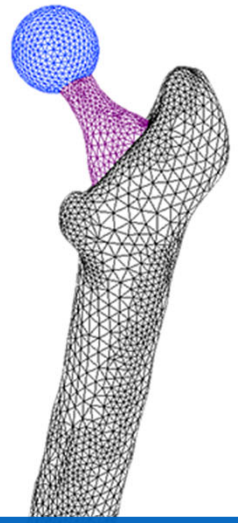
Research Center of Computational Mechanics, Inc.

http://www.rccm.co.jp/product/medical/mechanical-finder/en/index.html#English

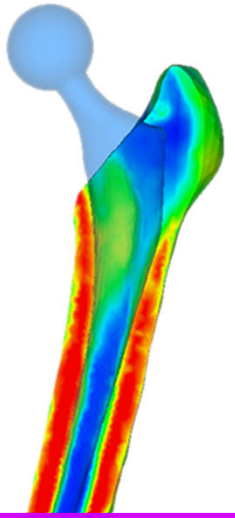
Mechanical Finder - All functions are in one package -

DICOM import

ROI extraction (Segmentation)

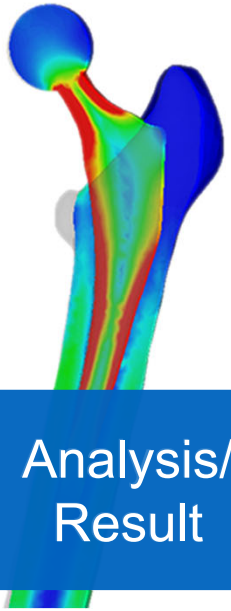


Mesh generation



Heterogeneous material properties

Boundary Condition

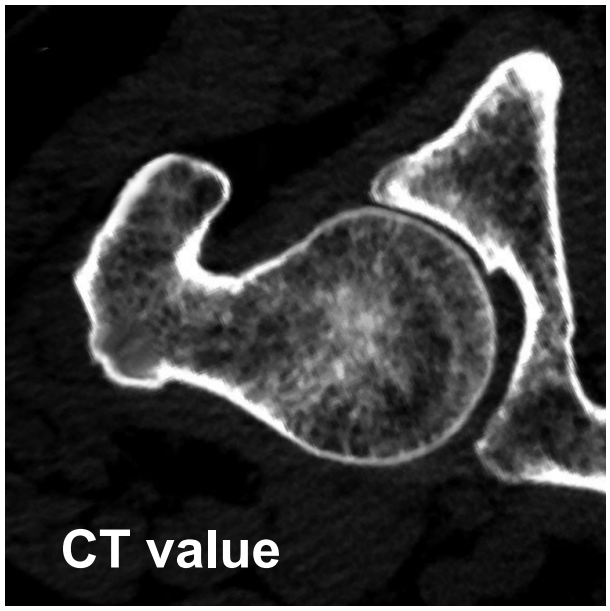


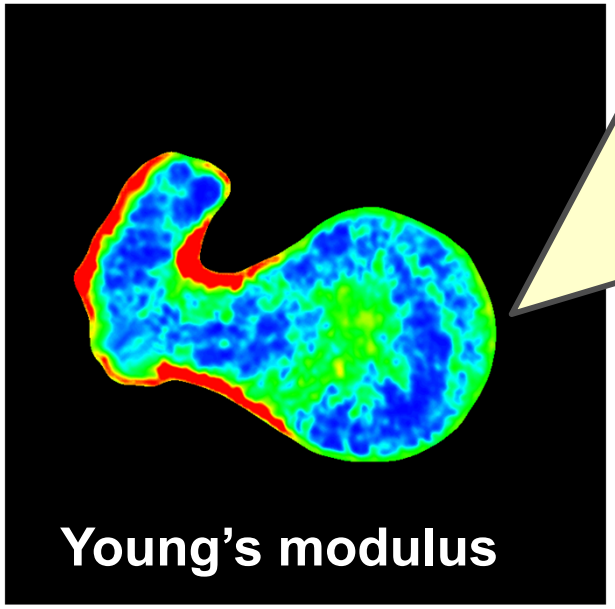
Analysis/ Result

- Static FEA
- Nonlinear fracture FEA

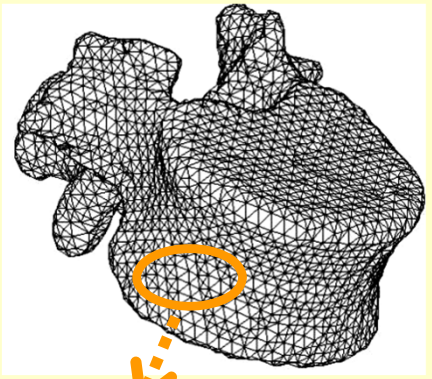
Mechanical Finder - Reflection of material property distribution -

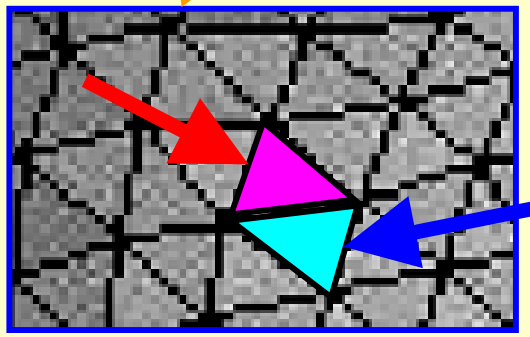
- Young's modulus of bone can be calculated based on bone density (CT values).
- Heterogeneous material properties reflecting the patient's degree of seriousness can be modeled.





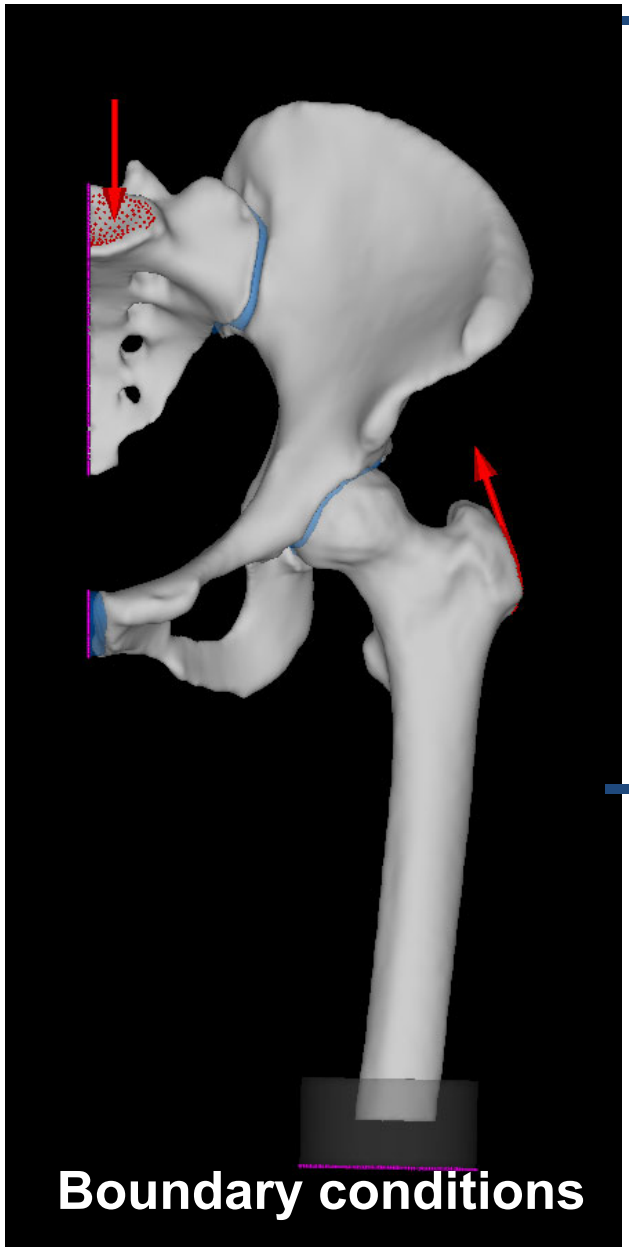
CT value ▷ density ▷ material properties



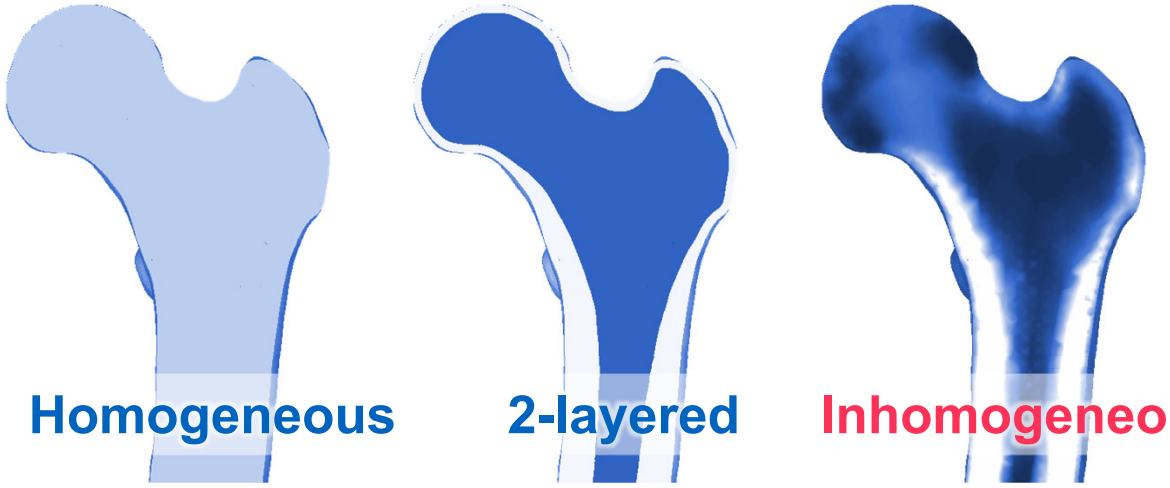


Define Young's modulus for an element one by one

Mechanical Finder - Reflection of material property distribution -

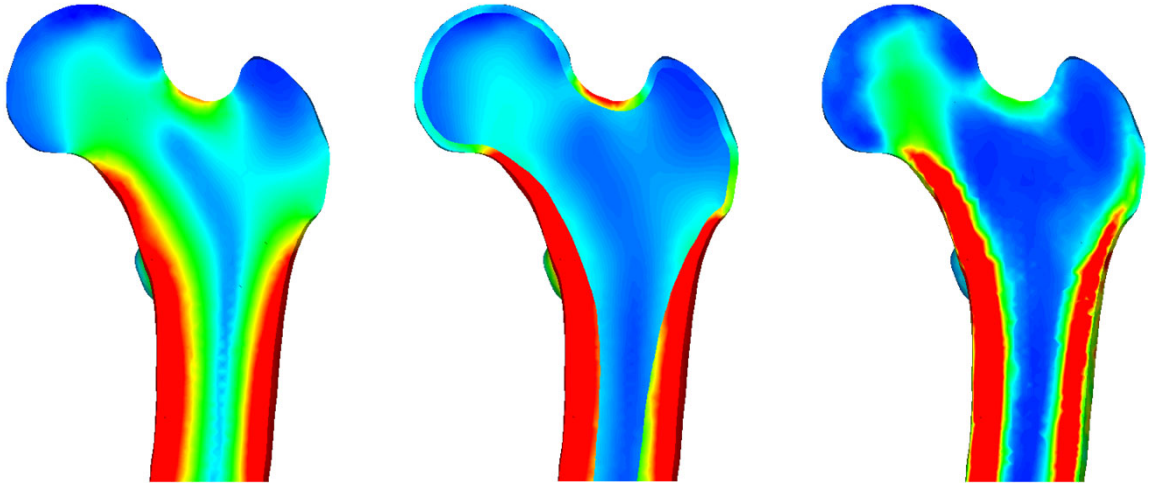


Young's modulus

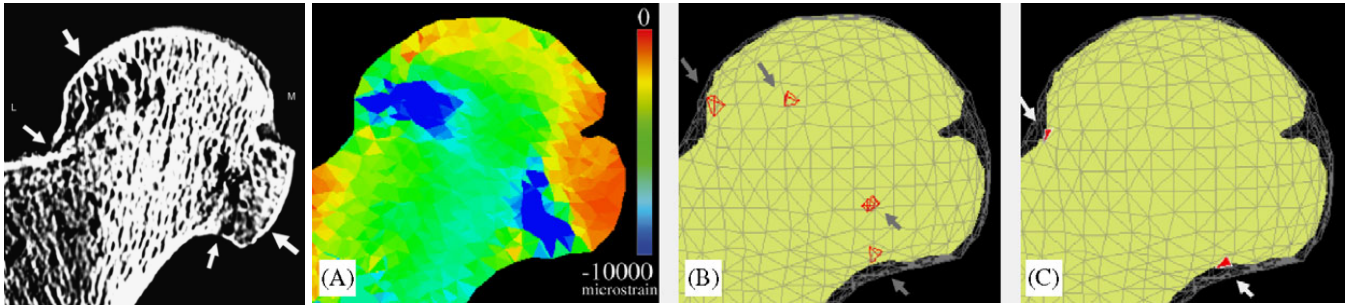


Analyze

Equivalent stress

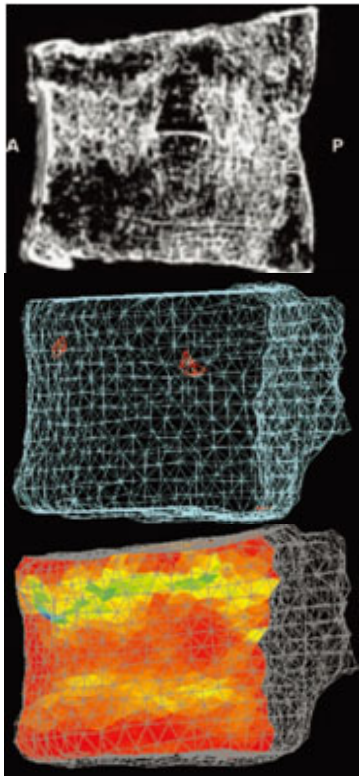


Mechanical Finder - Validation of the nonlinear fracture FEA -

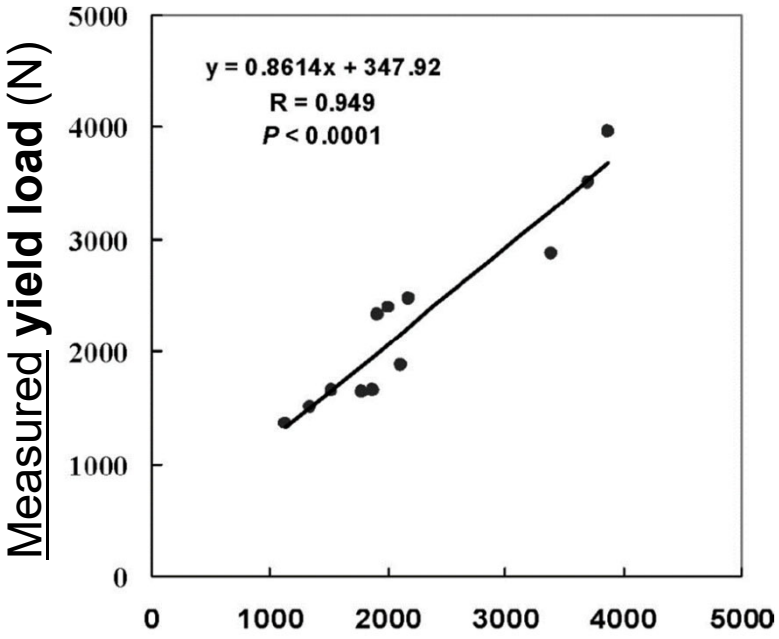


Fracture line (Femur)

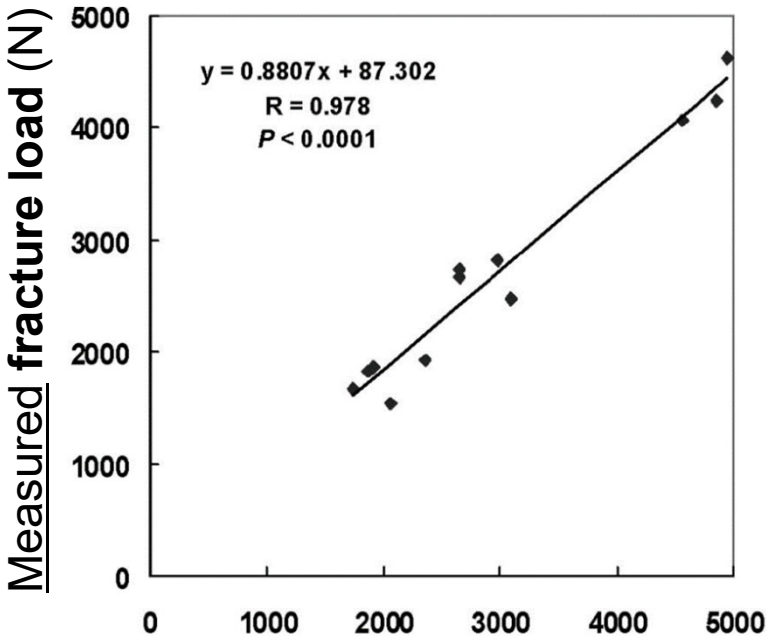
- K. Imai, et al., Spine, (2007), 1789-1794 .
- M. Bessho, et al., J. Biomechanics, (2007), 1745–1753.



Fracture line (Vertebra)



1 element **yield load** (N) (FEAs)

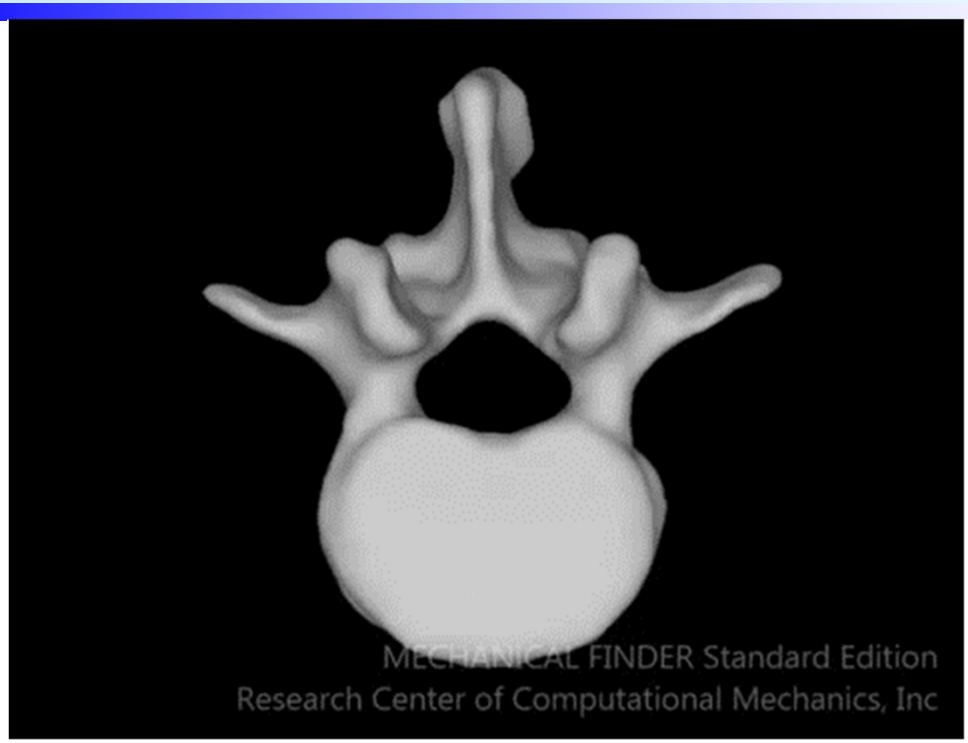


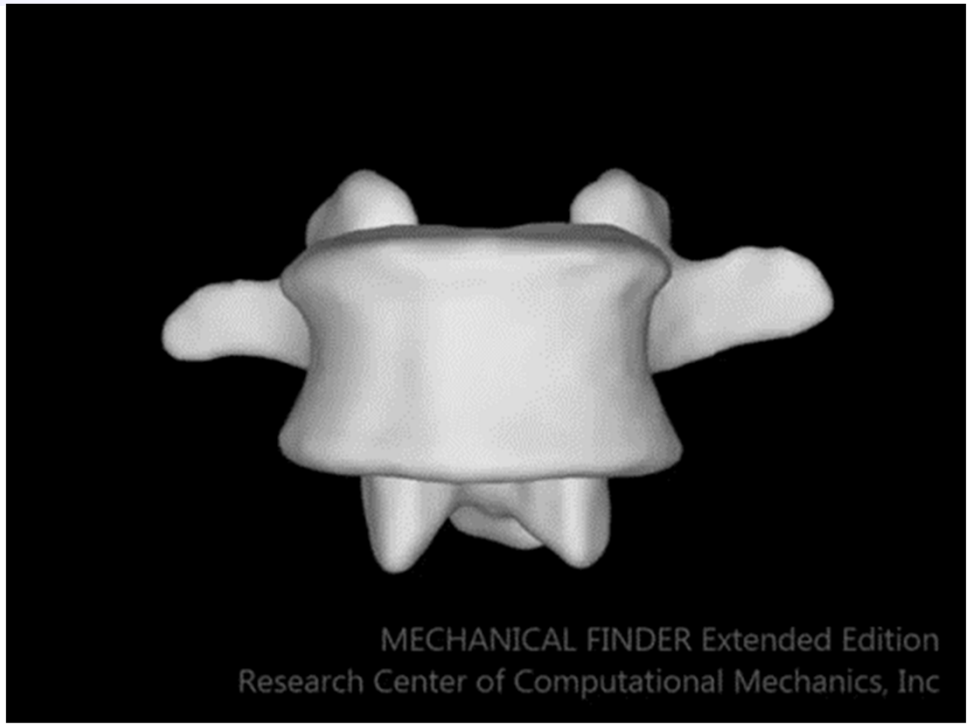
1 element **fracture load** (N) (FEAs)

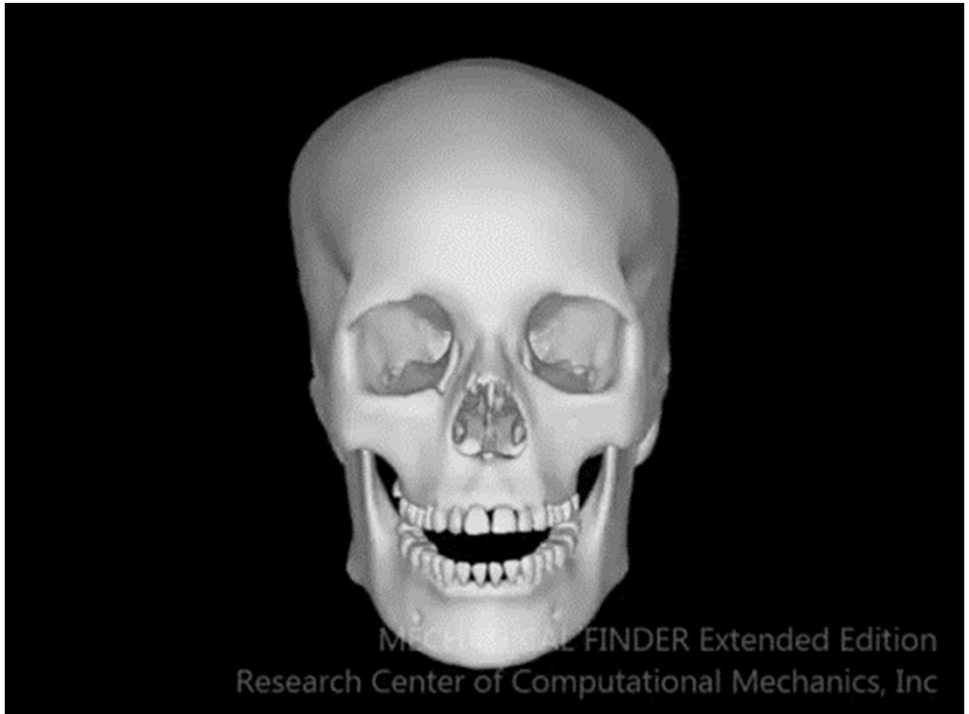
They confirmed positive correlations and validated the efficiency of the nonlinear FEAs.

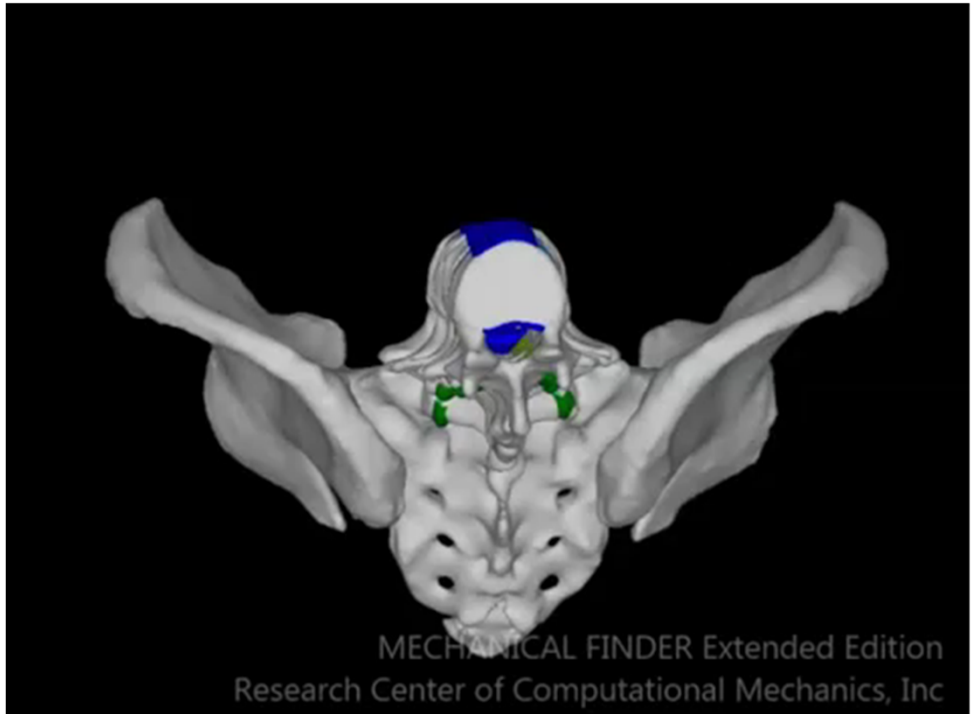
The nonlinear FEA technique in MF was valid.

Mechanical Finder - Examples of demonstrations -





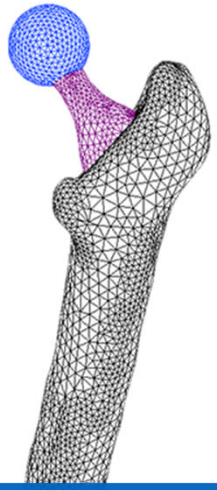




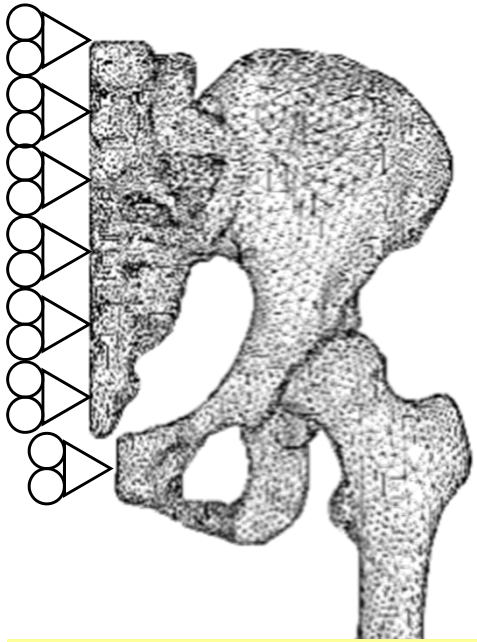
Need for boundary conditions

DICOM Import

ROI Extraction

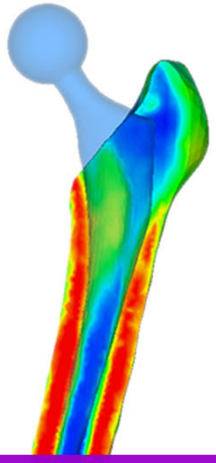


Mesh Generation



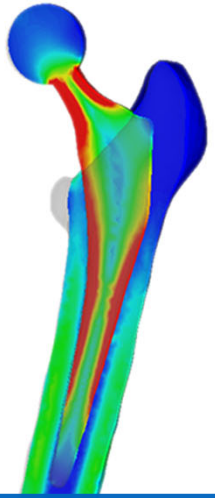
- We need BCs !

- We want to apply muscle forces to the FE model from AMS.



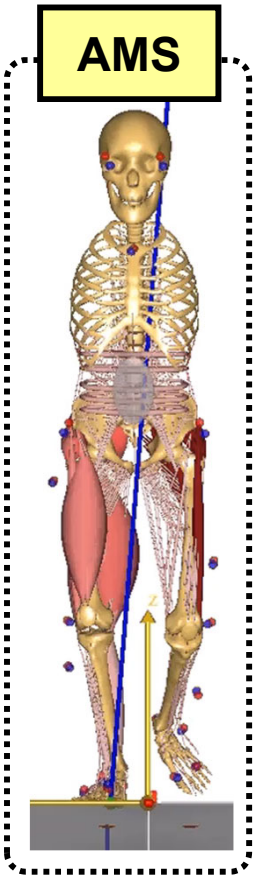
Heterogeneous Material Properties

Boundary Condition



Analysis/ Result

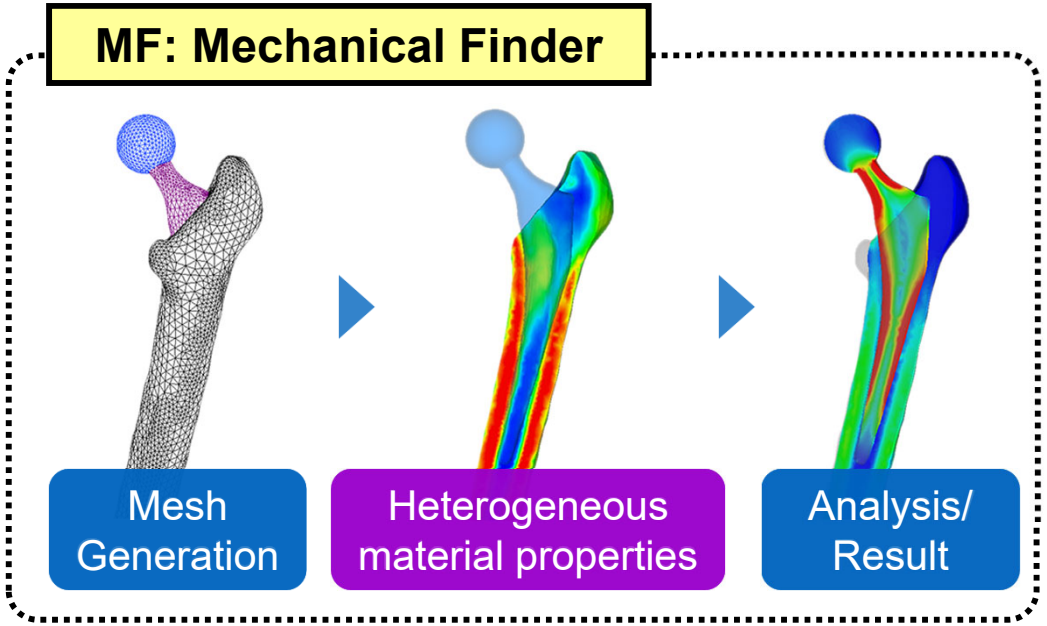
Towards the link between AMS and MF



?

Data converter

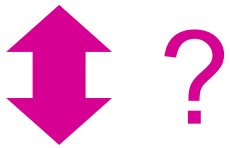
Convert_AnyBody



- Converts muscle forces data exported from AMS to MF format, but only for one timestep of the motion.
- Searches for the nearest node on FE model for each muscle point.
- MF only accepts the top 20 loading conditions due to the design of the graphical user interface.
- Also exports all muscle forces from AMS as text data.

Towards the link between AMS and MF

	Advantages	Disadvantages
Mechanical Finder (MF) (RCCM., Inc.)	◆ Easy segmentation ◆ Reflection of heterogeneous Young's modulus	◆ only accepts the top 20 loading conditions.
Femap/Nastran (General FEA pre/post processor and solver, Simens)	◆ Function-rich pre/post processor	◆ FEA with heterogeneous material properties takes a long time or is impossible.
FrontISTR (Large-scale FEA solver on parallel PC cluster, open free code, made by University of Tokyo, Japan)	◆ A large-scale FEA with heterogeneous material properties	◆ Pre/Post processors are poorer than commercial code.



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AMS

CT (DICOM)

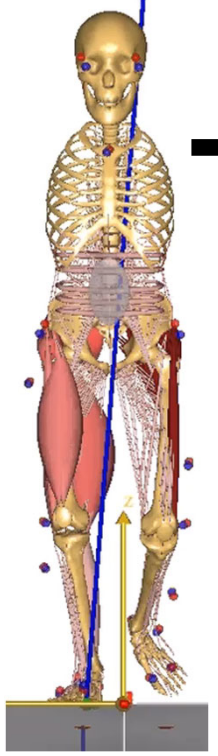
c3d

(Mimics)

stl

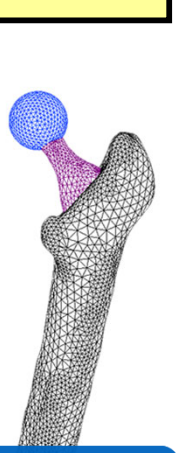
- Morphing
- Scaling

AMS

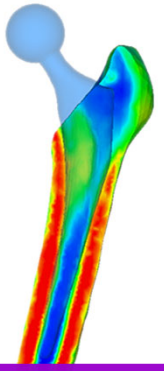


Muscle forces **on the CT flame**

MF

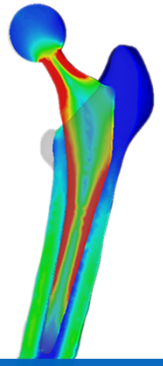


Mesh Generation



Heterogeneous material properties

Boundary Condition



Analysis/ Result

➢ Limitation up to 20 loading conditions

AMS2MF

Convert_AnyBody

MF2FrontISTR

● ***FEA***

FrontISTR

FEA system on the PC cluster (in Ryukoku Univ.)

FrontISTR2ParaView

ParaView

Free software for visualization

■ Search the nodes on a FE model to apply force for all time steps

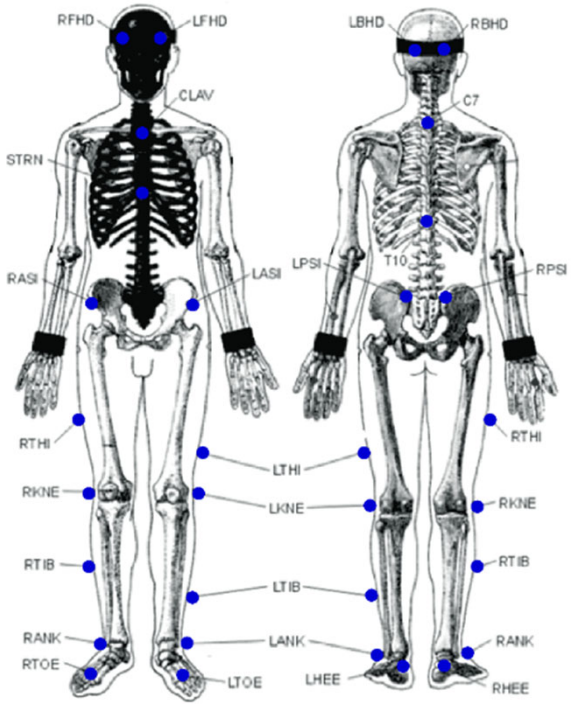
● ***Visualize the BCs***

MF2Femap

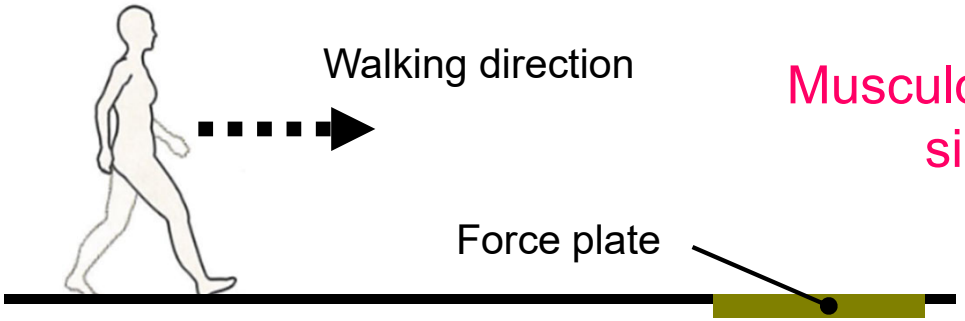
Femap/Nastran

General pre-processor

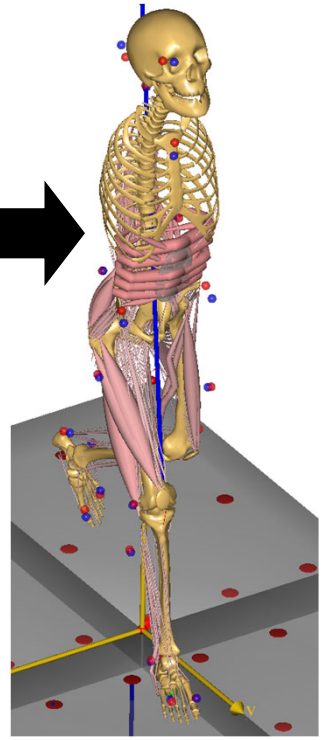
Gait analysis and FEA of a hip osteoarthritis patient



- Gait motion and ground reaction forces were measured using 25 markers (Vicon 512).
- 318 muscles were defined by scaling to the body size (Anybody Modeling System).



Musculoskeletal simulation



Objective function: $$G = \sum_{i=1}^{n^{(m)}} \left(\frac{f_i^{(m)}}{N_i} \right)^3 \Rightarrow \textbf{min.}$$

Subject to: $$\boldsymbol{M} = \boldsymbol{rf}, \quad \sum \boldsymbol{f} = 0, \quad f_i^{(m)} \geq 0, \quad i \in \{1,..,n\}$$

$\boldsymbol{M}$: Joint moments $\quad \boldsymbol{r} = \left[\boldsymbol{r}^{(m)} \quad \boldsymbol{r}^{(j)} \right]$: Moment arms $\quad \boldsymbol{f} = \left[\boldsymbol{f}^{(m)} \quad \boldsymbol{f}^{(j)} \right]$: Forces

$\boldsymbol{m}$: for muscles, $\quad \boldsymbol{j}$: joints, $\quad N_i$: Maximum isometric force,

$f_i^{(m)}$: Muscle force, $\quad \boldsymbol{n}^{(m)}$: number of muscles

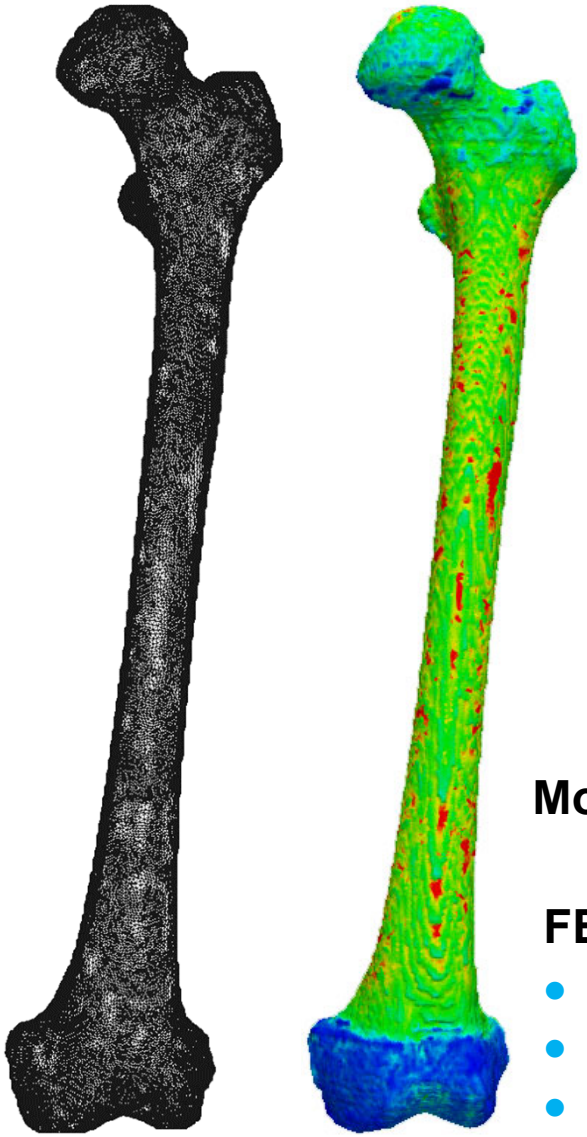
Methods

Patient	Age	Height	Weight
Japanese female	68	1.55 m	56 kg

CT images (DICOM) → c3d

- Before THA
- 3 months after THA
- 1 year after THA

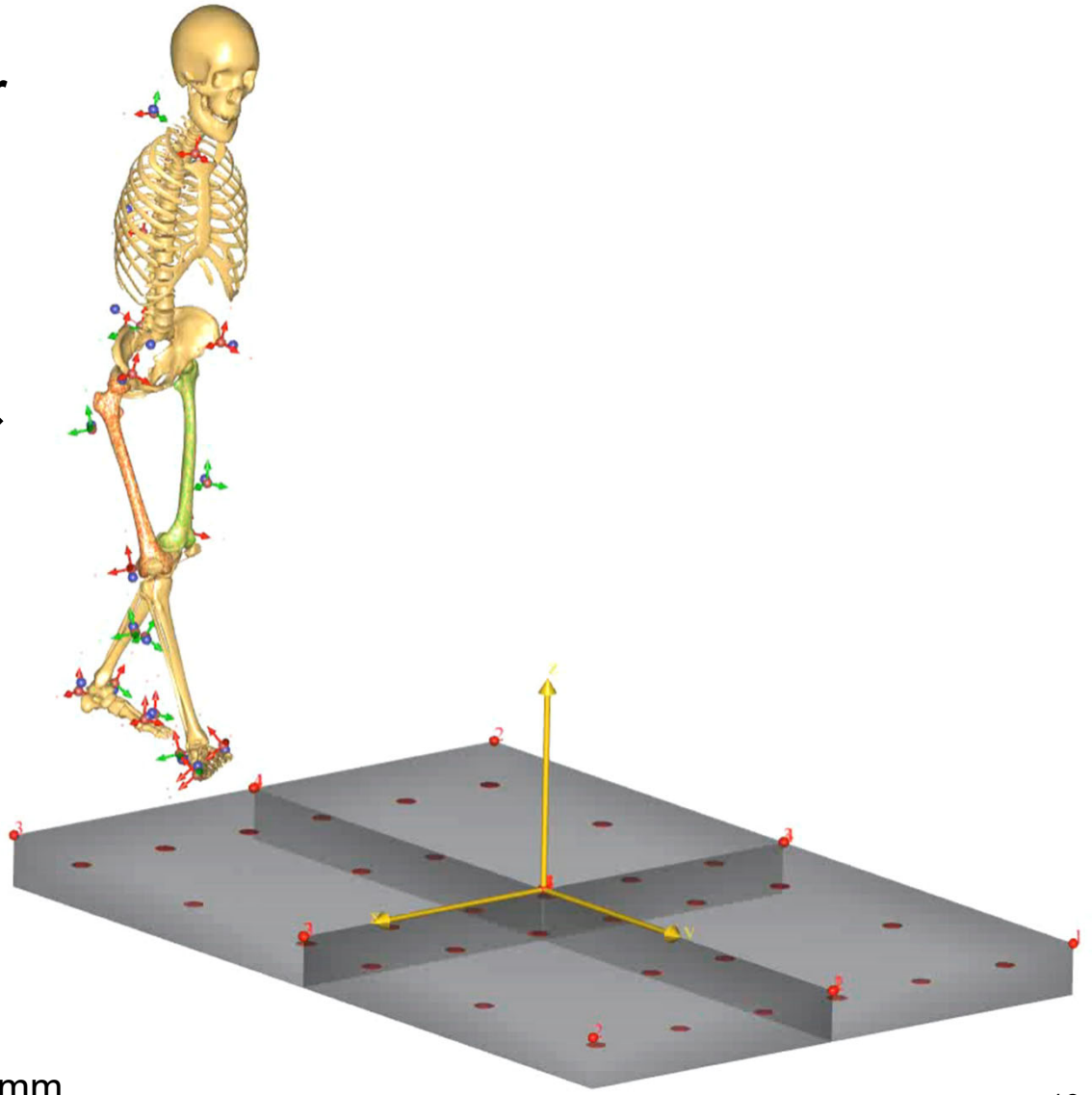
- **Left femur**



- **Right femur**
  - Mirrored

Morphing

Young's Modulus (GPa)

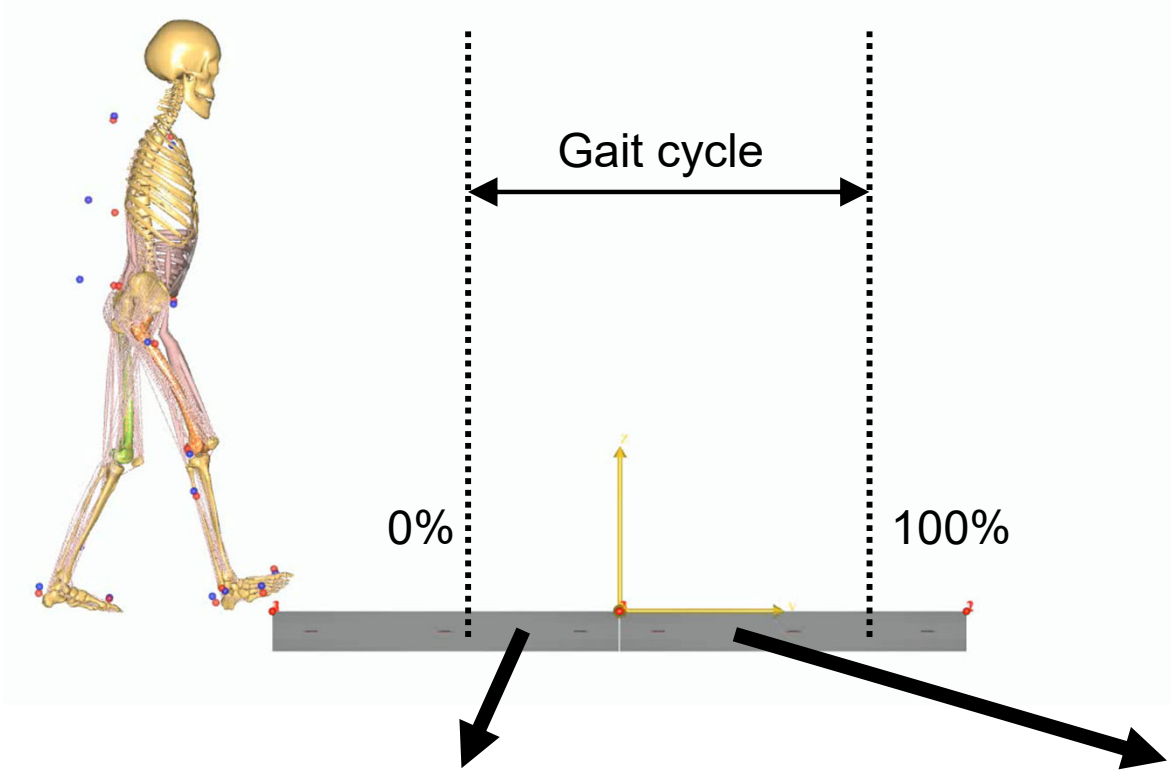


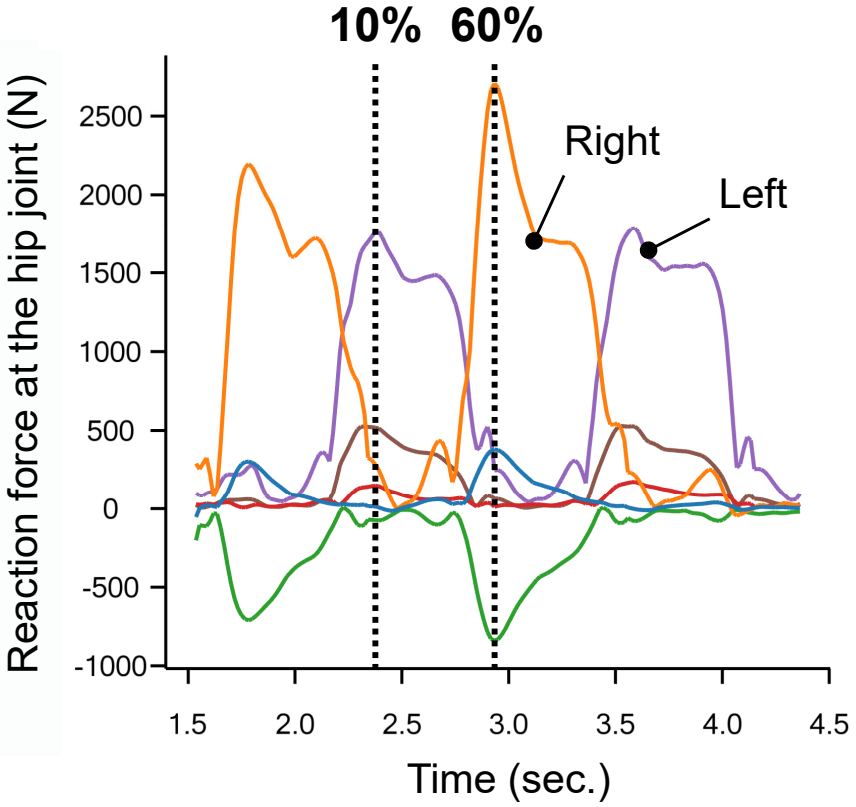
FE model

- Nodes: 202,751
- Elements: 969,070
- Element length: 1-4 mm

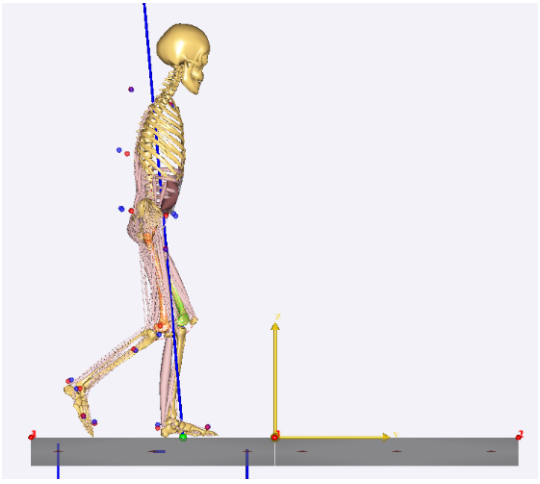
Analysis targets

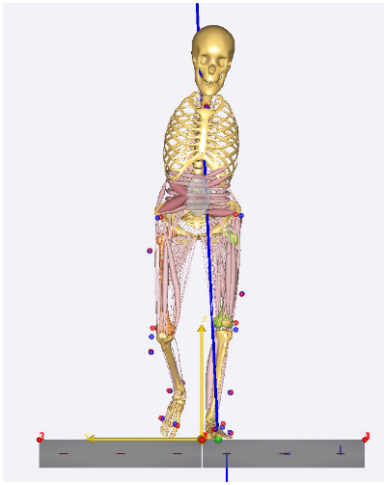
Before THA



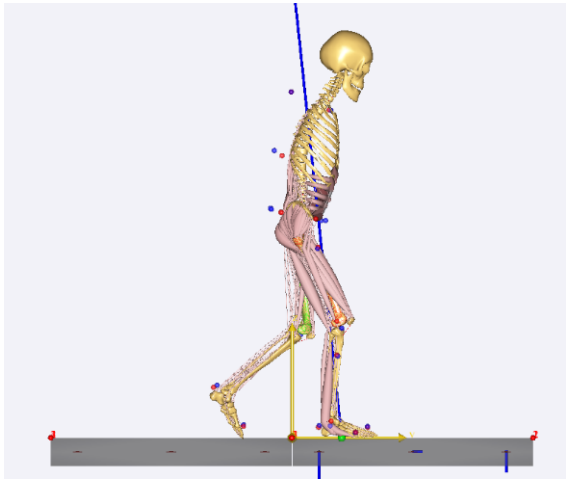


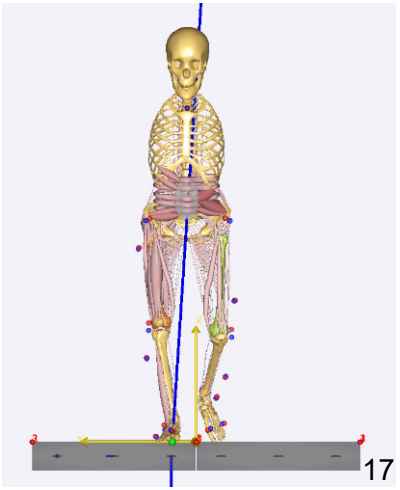
- **10%** : Time point where the right foot left the ground





- **60%** : Time point where the left foot left the ground

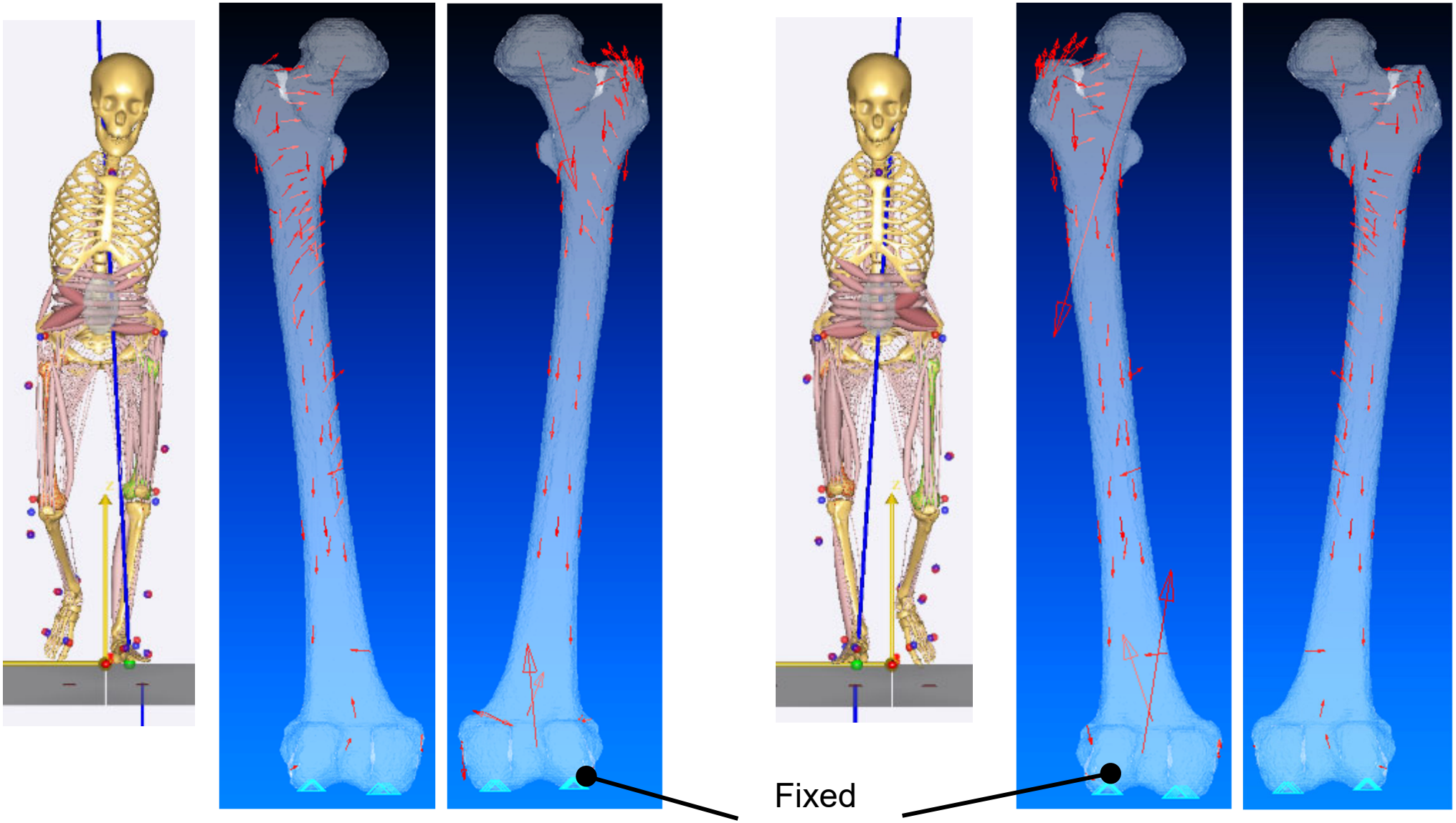




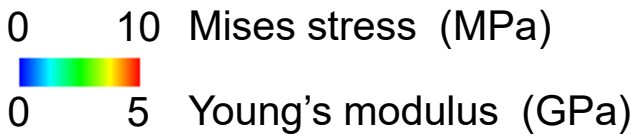
Visualization of BCs on the FE model *- before THA -*

- **10%** : Time point where the right foot left the ground

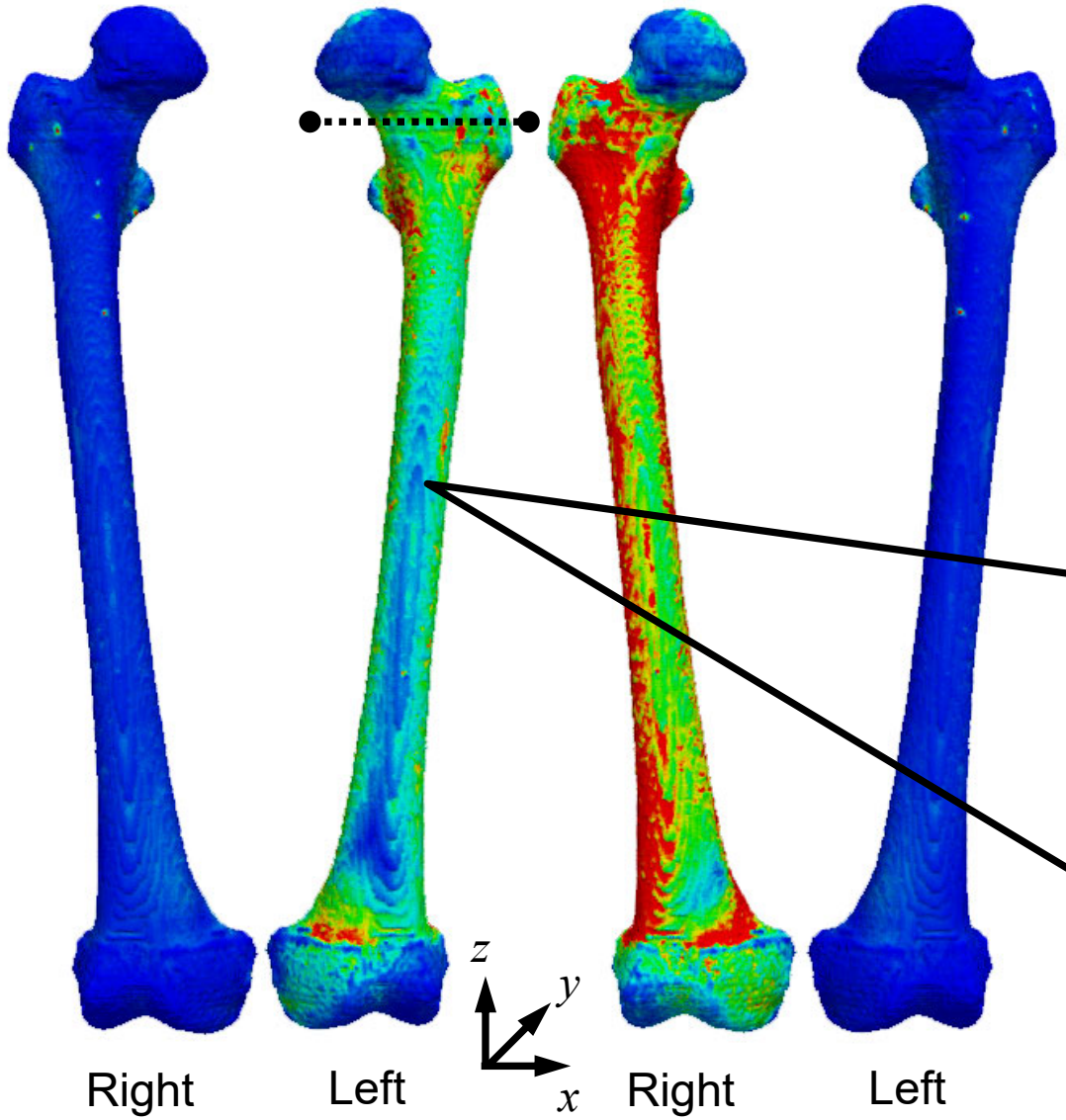
- **60%** : Time point where the left foot left the ground



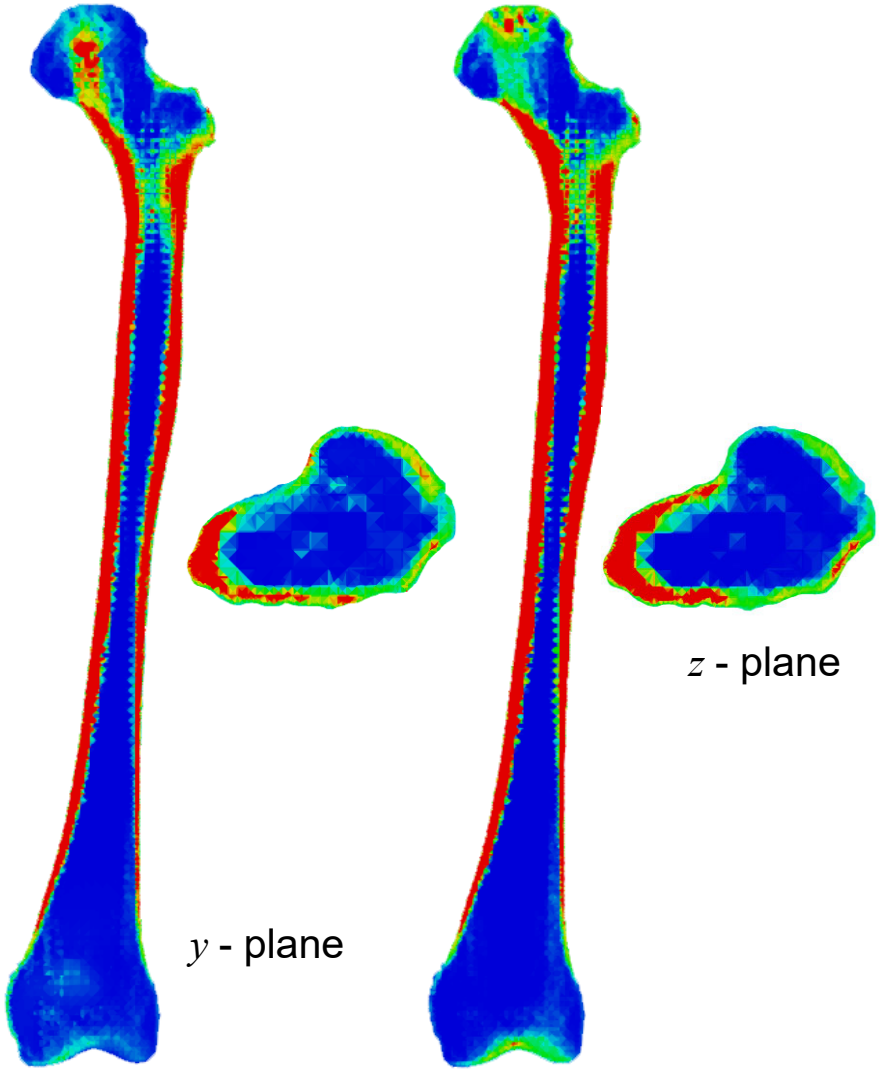
Results - Stress distribution before THA -



- Mises stress distribution
  - **10% :**
  - **60% :**

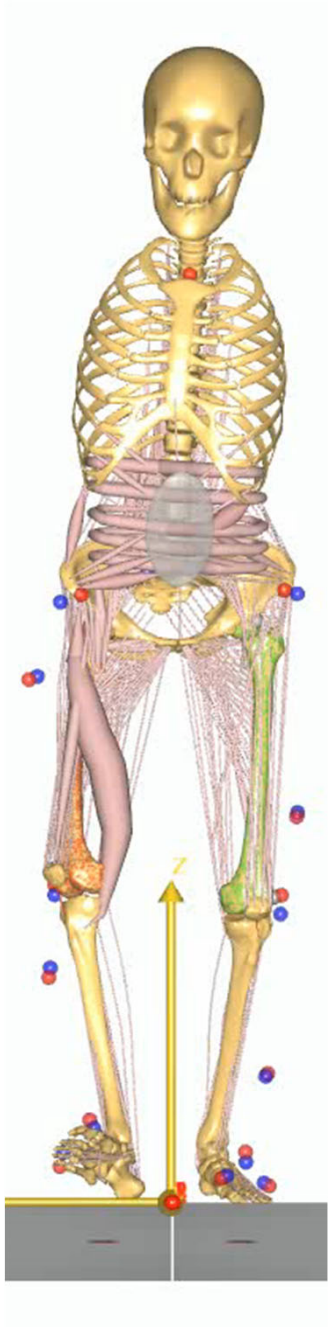


Cutting plane

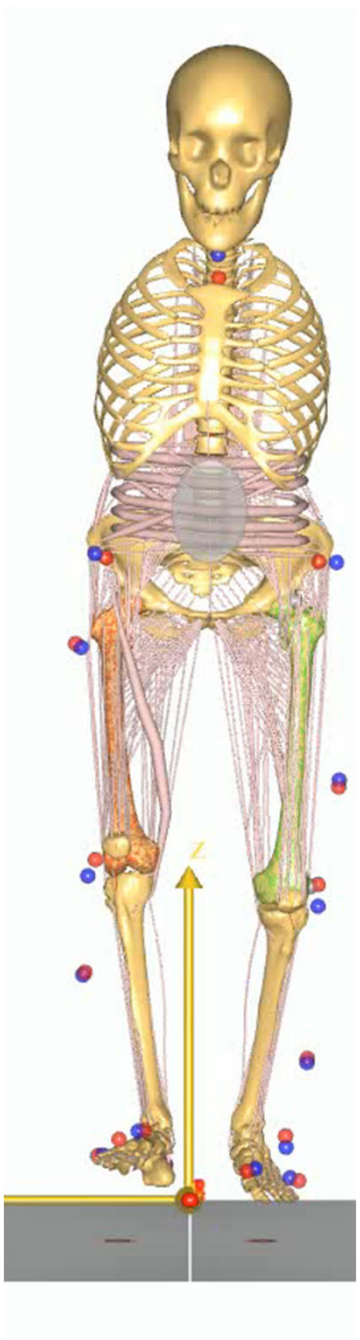


- Mises stress distribution
- Young's modulus distribution

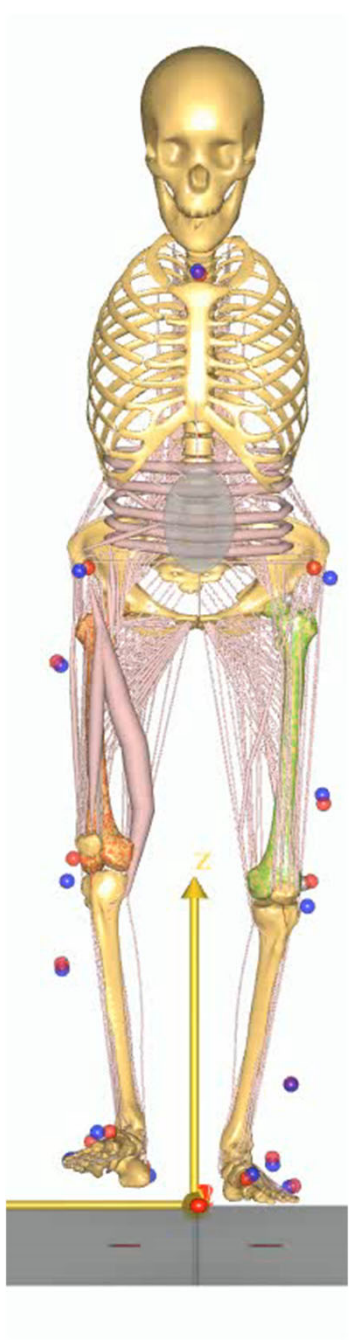
Walking postures of the patient before and after THA



Before THA



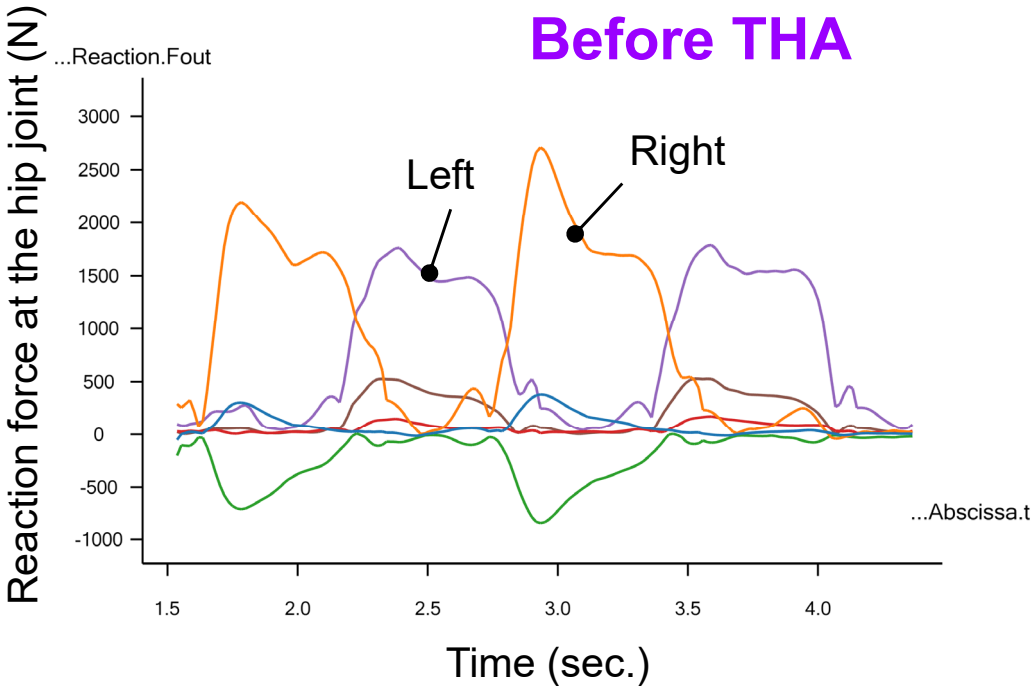
3 months after THA



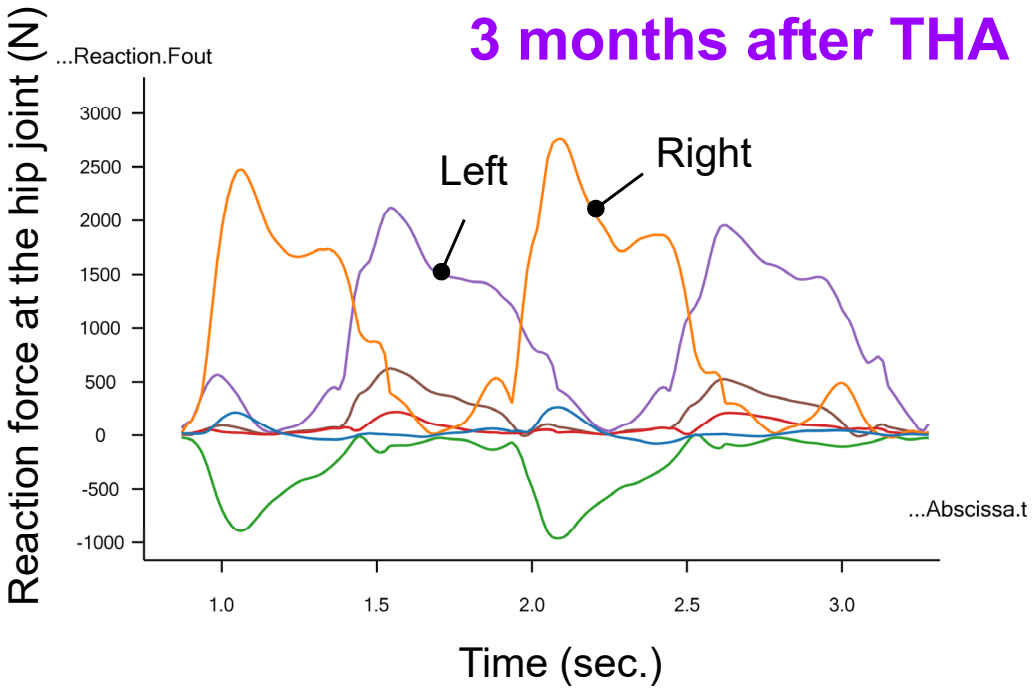
1 year after THA

Results - Change in hip joint reaction forces -

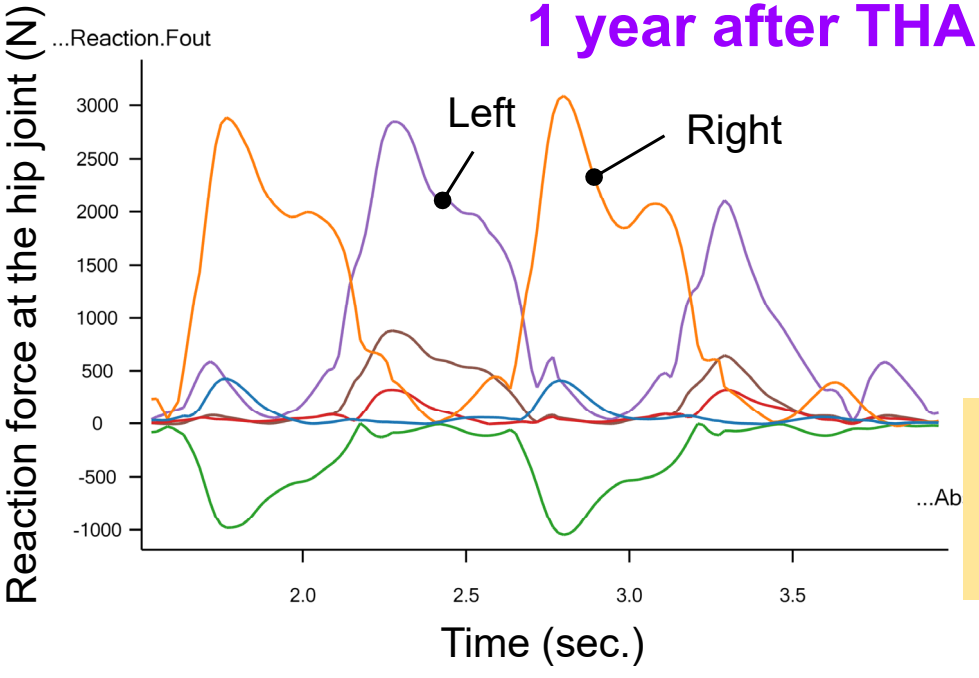
Before THA



3 months after THA



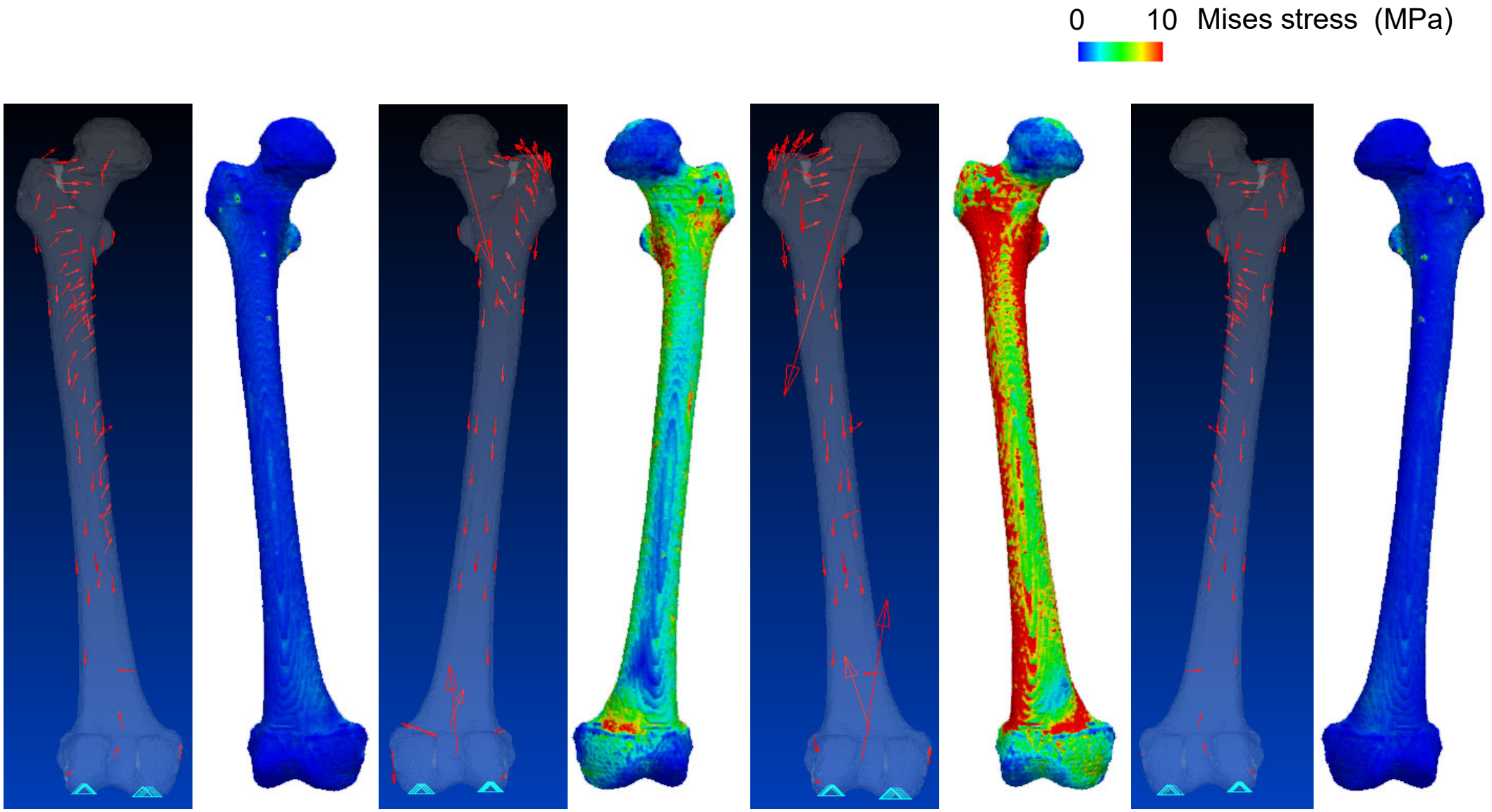
1 year after THA



- : Right (Inferior direction)
- : Right (Lateral direction)
- : Right (Anterior direction)
- : Left (Inferior direction)
- : Left (Lateral direction)
- : Left (Anterior direction)

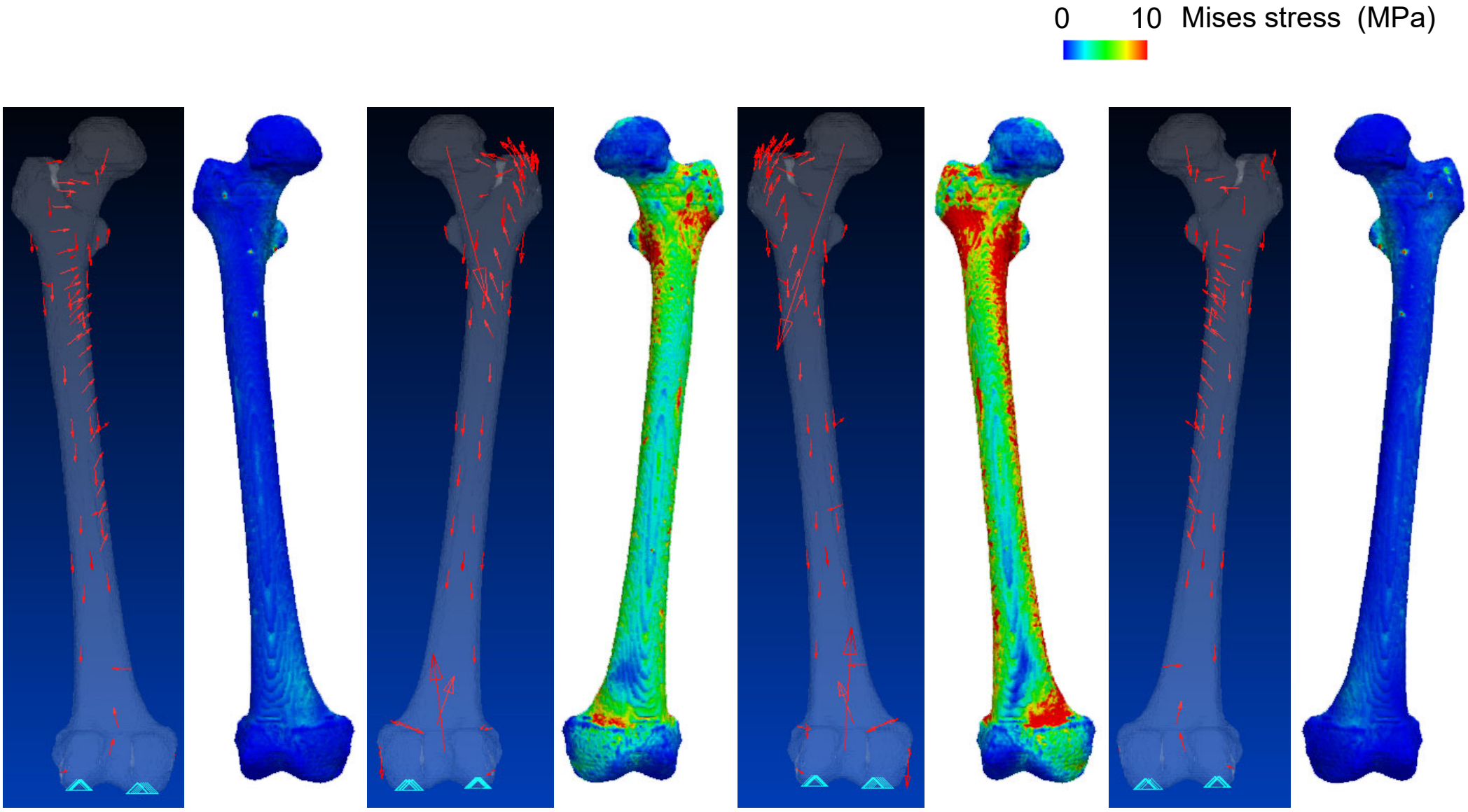
Unequal joint reaction forces improved to a balanced state after THA.

Results - Stress distribution and boundary conditions -



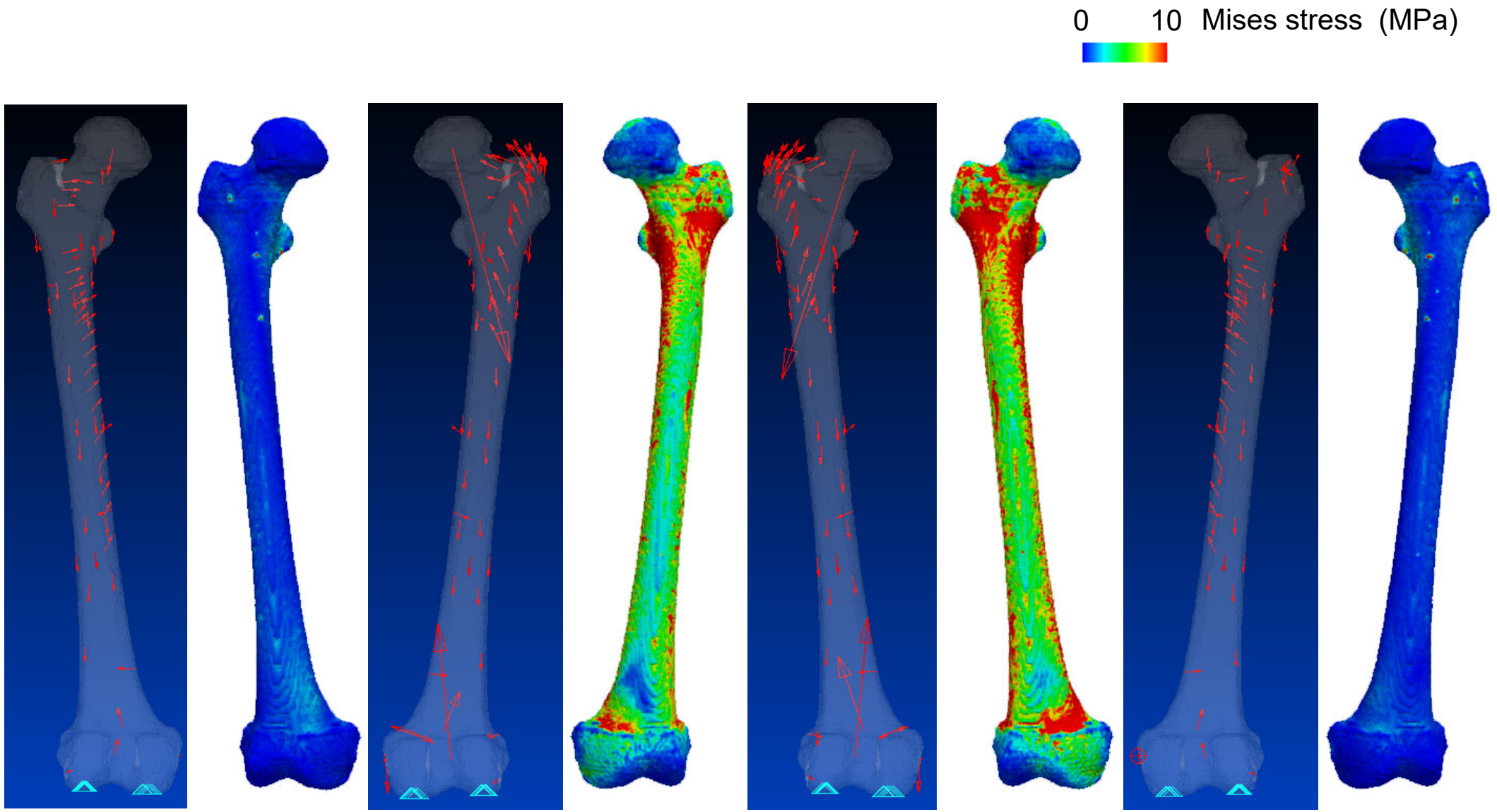
Before THA

Results - Stress distribution and boundary conditions -



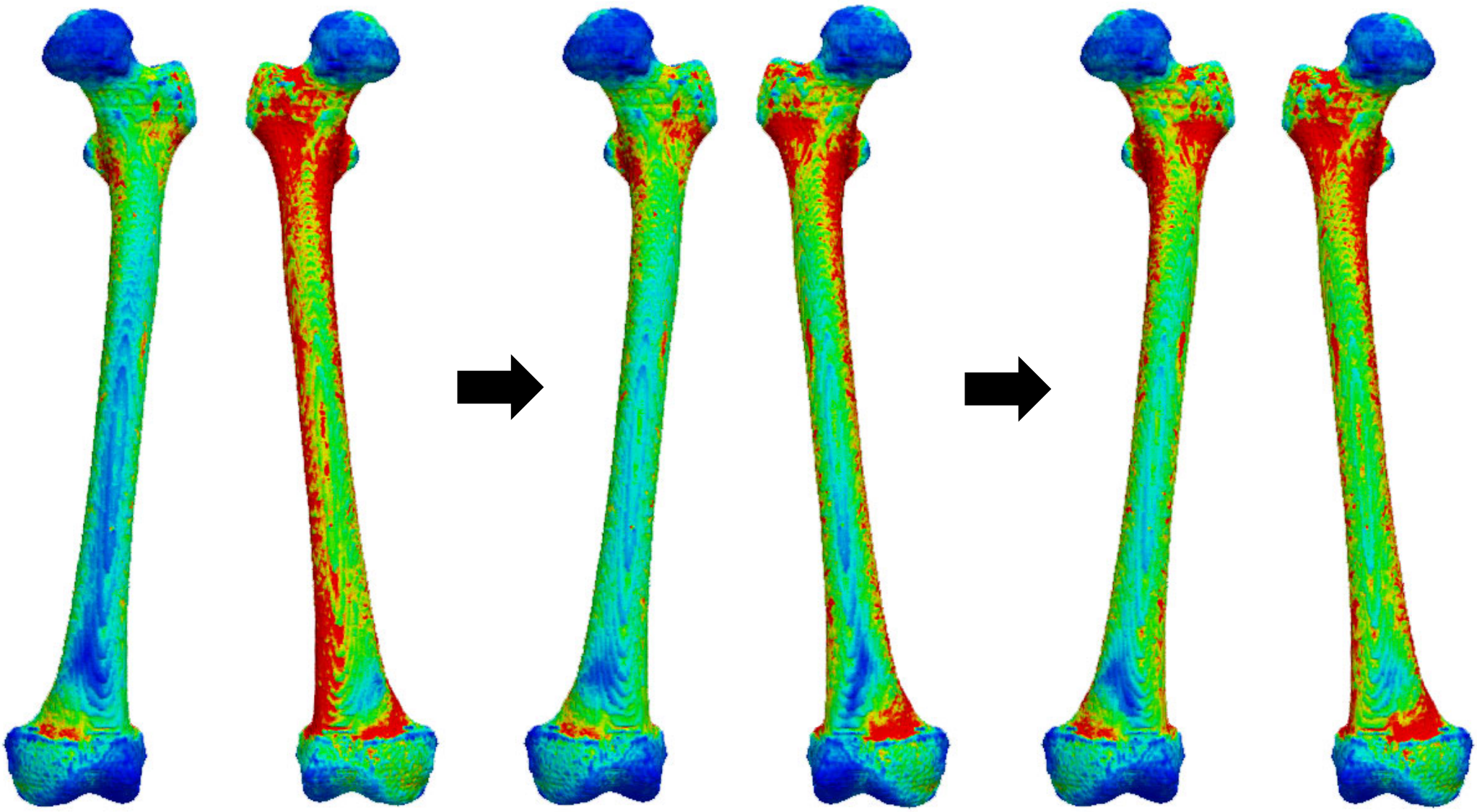
3 months after THA

Results - Stress distribution and boundary conditions -



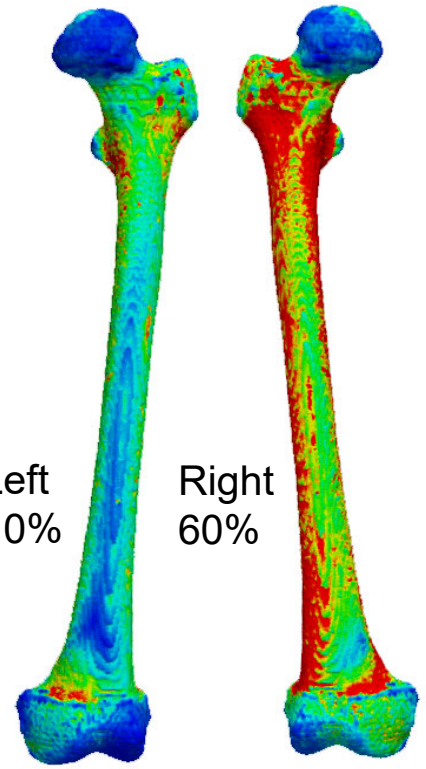
1 year after THA

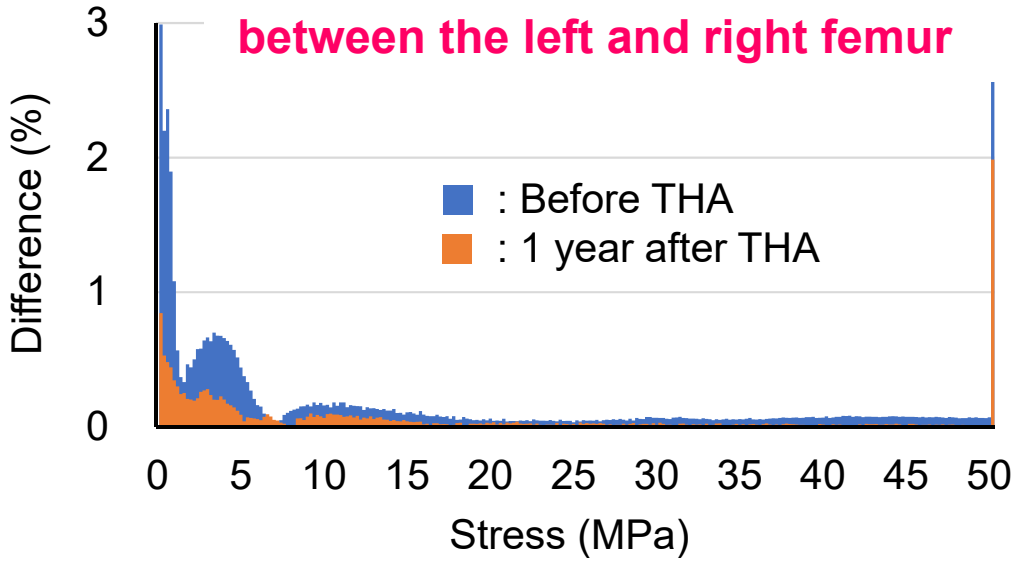
Results - Change in stress distribution -

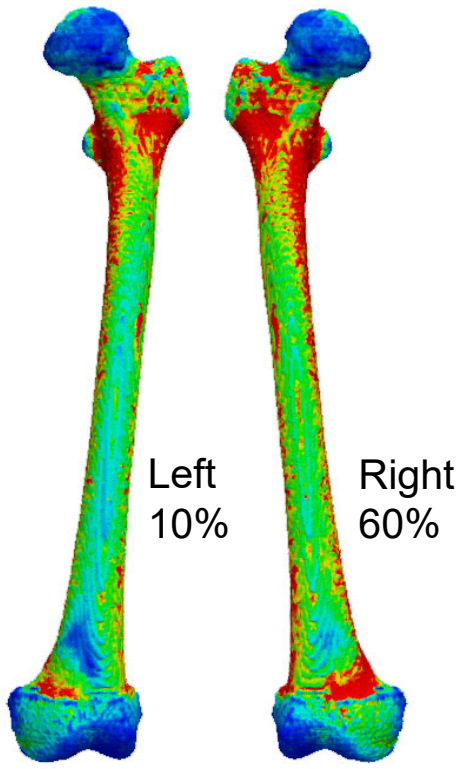


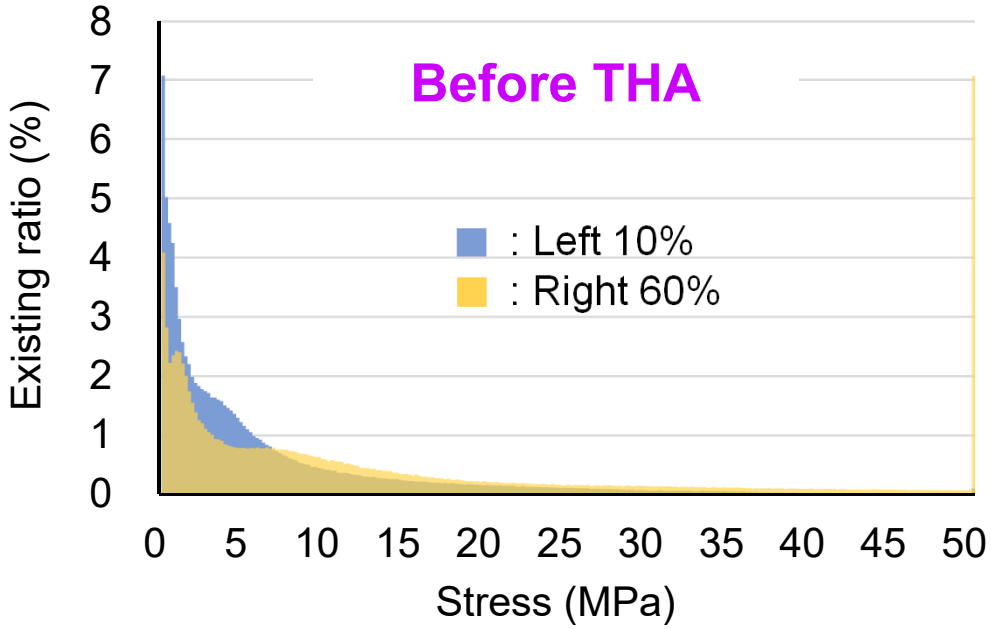
Unequal stress distribution → Balanced distribution

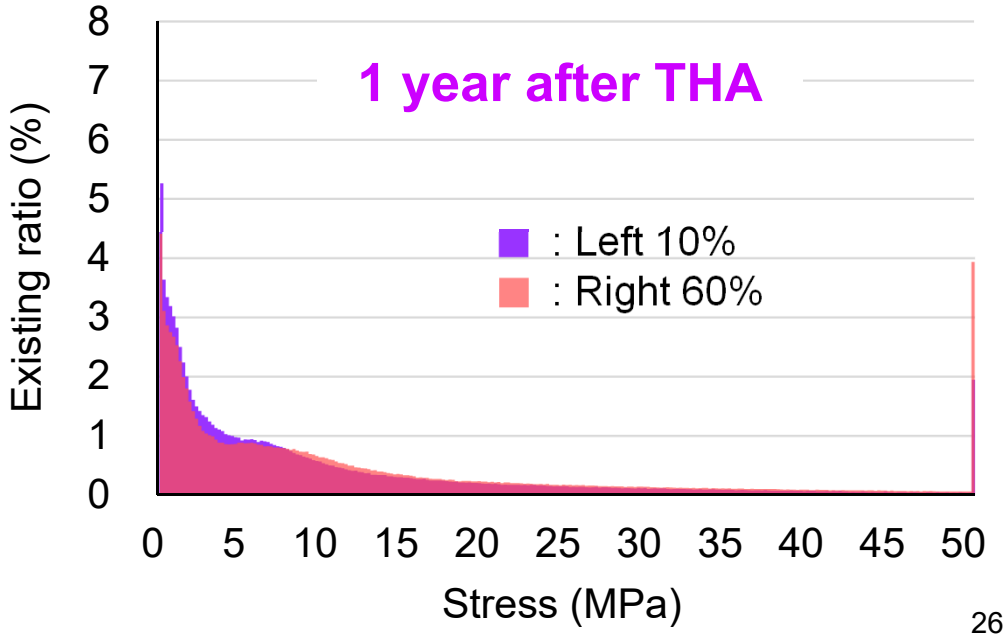
Results - Change in stress distribution -



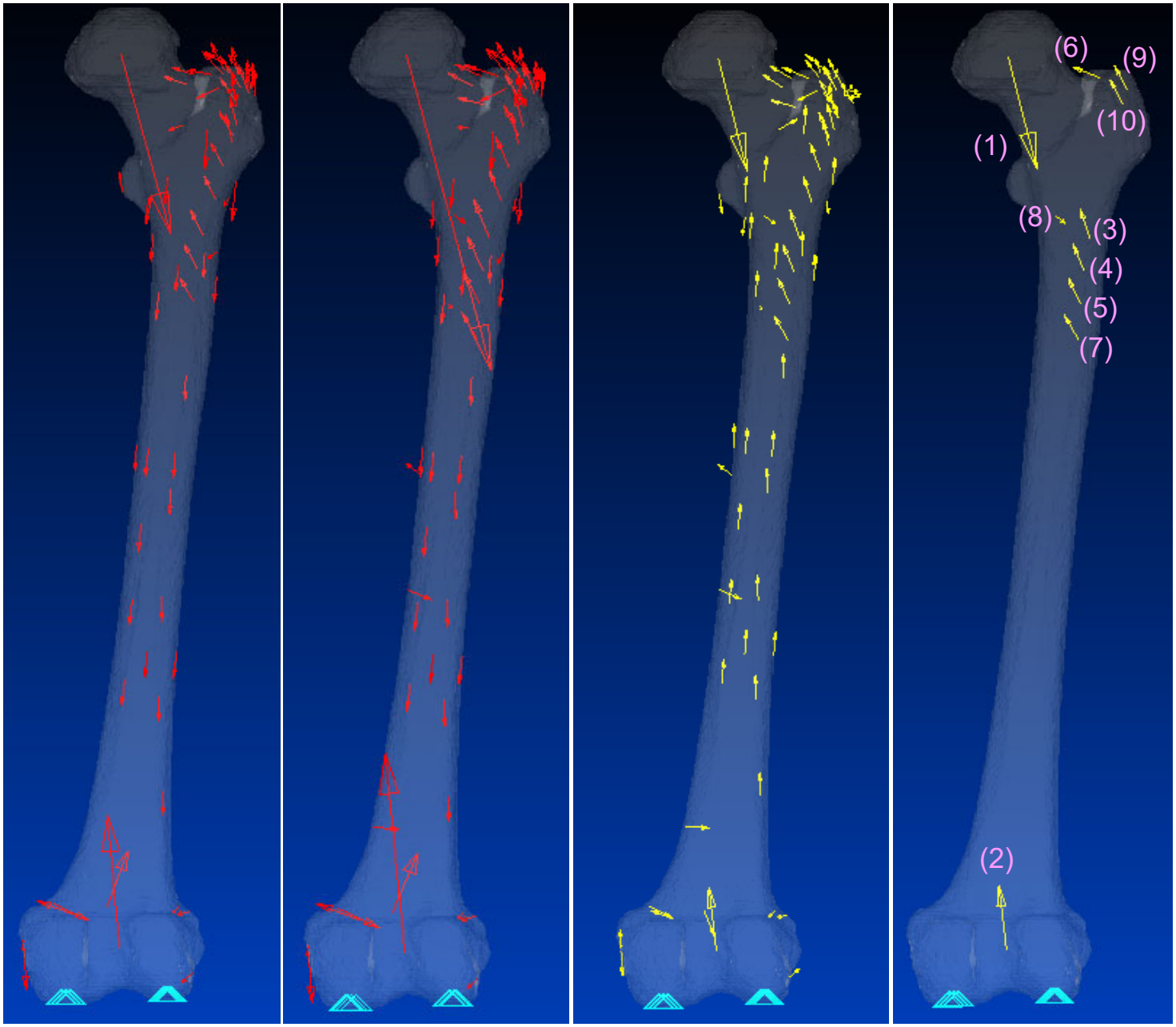








Results - Difference of BCs between before/after THA (Left femur) -



(1) Jnt.Hip.Constraints.Reaction

(2) Jnt.Knee.Constraints.Reaction

(3) GluteusMediusPosterior3

(4) GluteusMediusPosterior4

(5) Mus.GluteusMediusPosterior5

(6) Mus.ObturatorInternus1-5

(7) GluteusMediusPosterior6

(8) Sartorius1

(9) GluteusMaximusSuperior2

(10) GluteusMaximusSuperior3

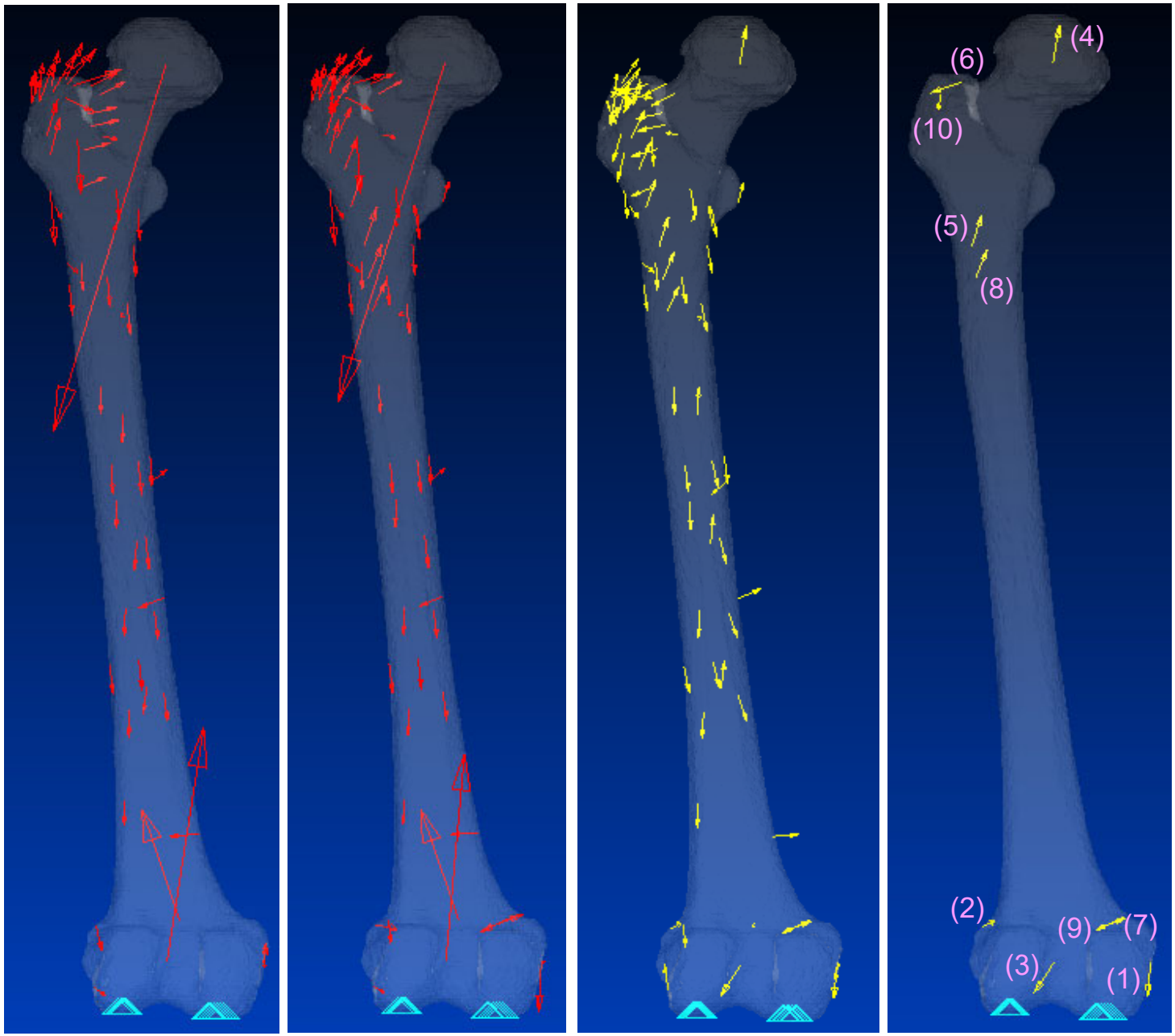
BCs (before THA)

BCs (1 year after THA)

Difference (All BCs)

Difference (Top10 BCs)

Results - Difference of BCs between before/after THA (Right femur) -



(1) GastrocnemiusLateralis1, GastrocnemiusMedialis1, Plantaris1

(2) GastrocnemiusLateralis1

(3) RectusFemoris2

(4) RectusFemoris2

(5) GluteusMaximusInferior1

(6) ObturatorInternus1-6

(7) GastrocnemiusMedialis1

(8) GluteusMaximusInferior2

(9) GastrocnemiusMedialis1

(10) GluteusMinimusAnterior1

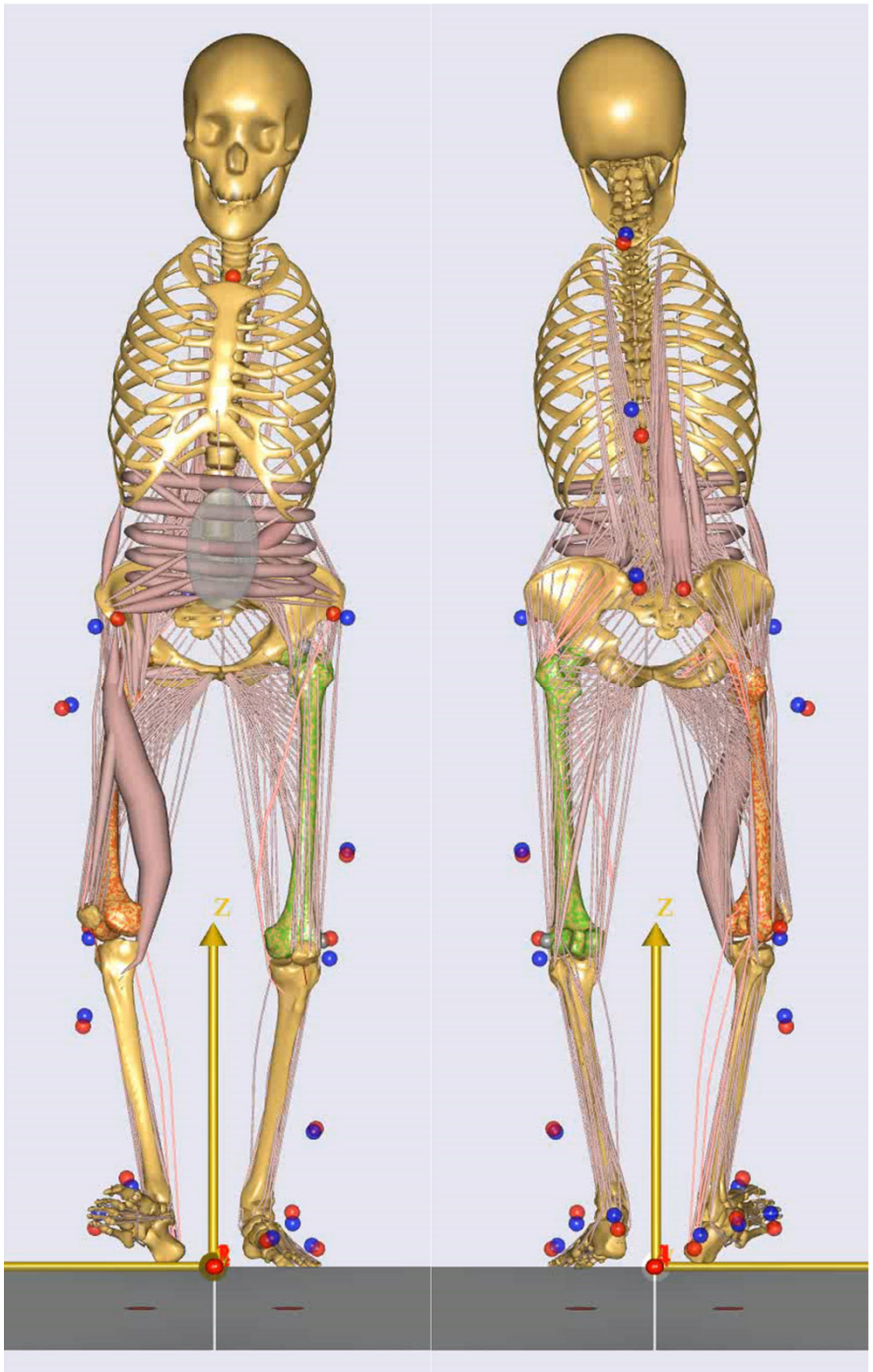
BCs (before THA)

BCs (1 year after THA)

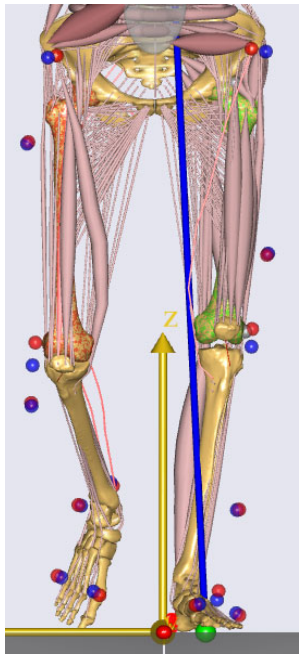
Difference (All BCs)

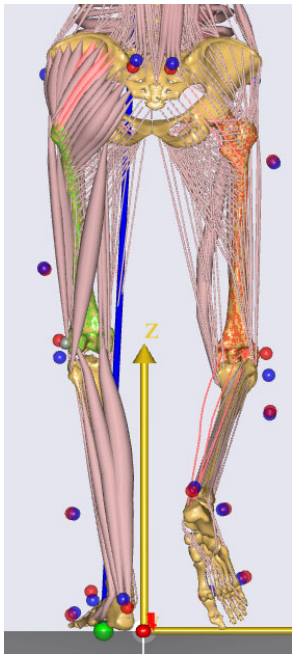
Difference (Top10 BCs)

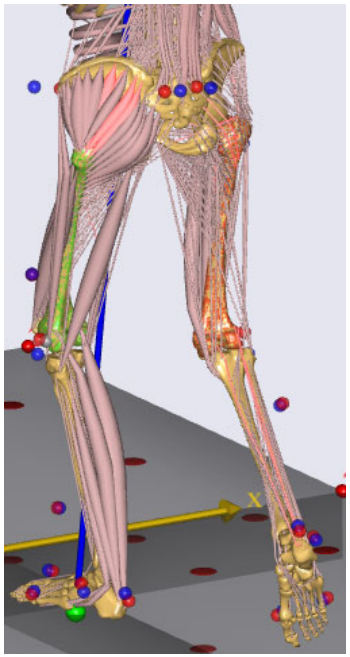
Results - The top 10 muscles which changed significantly -



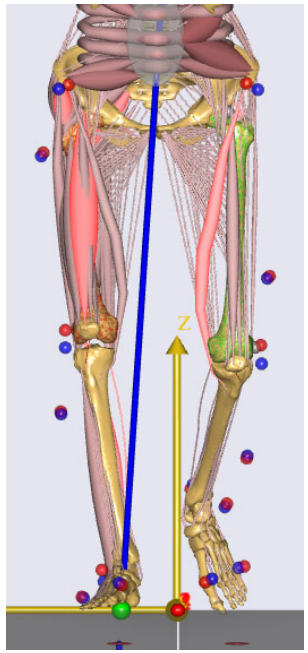
10%

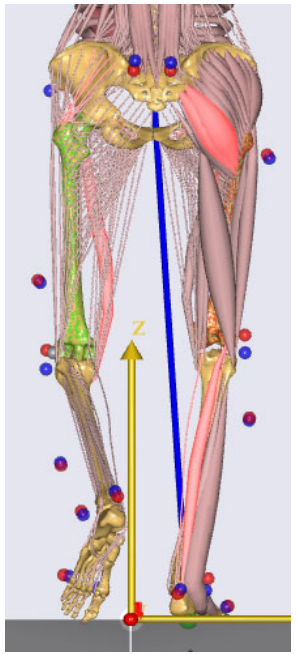


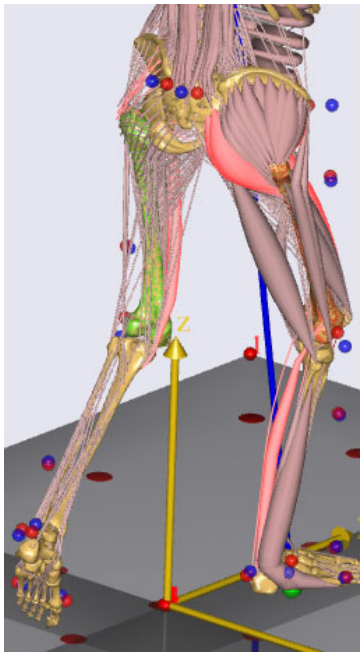




60%



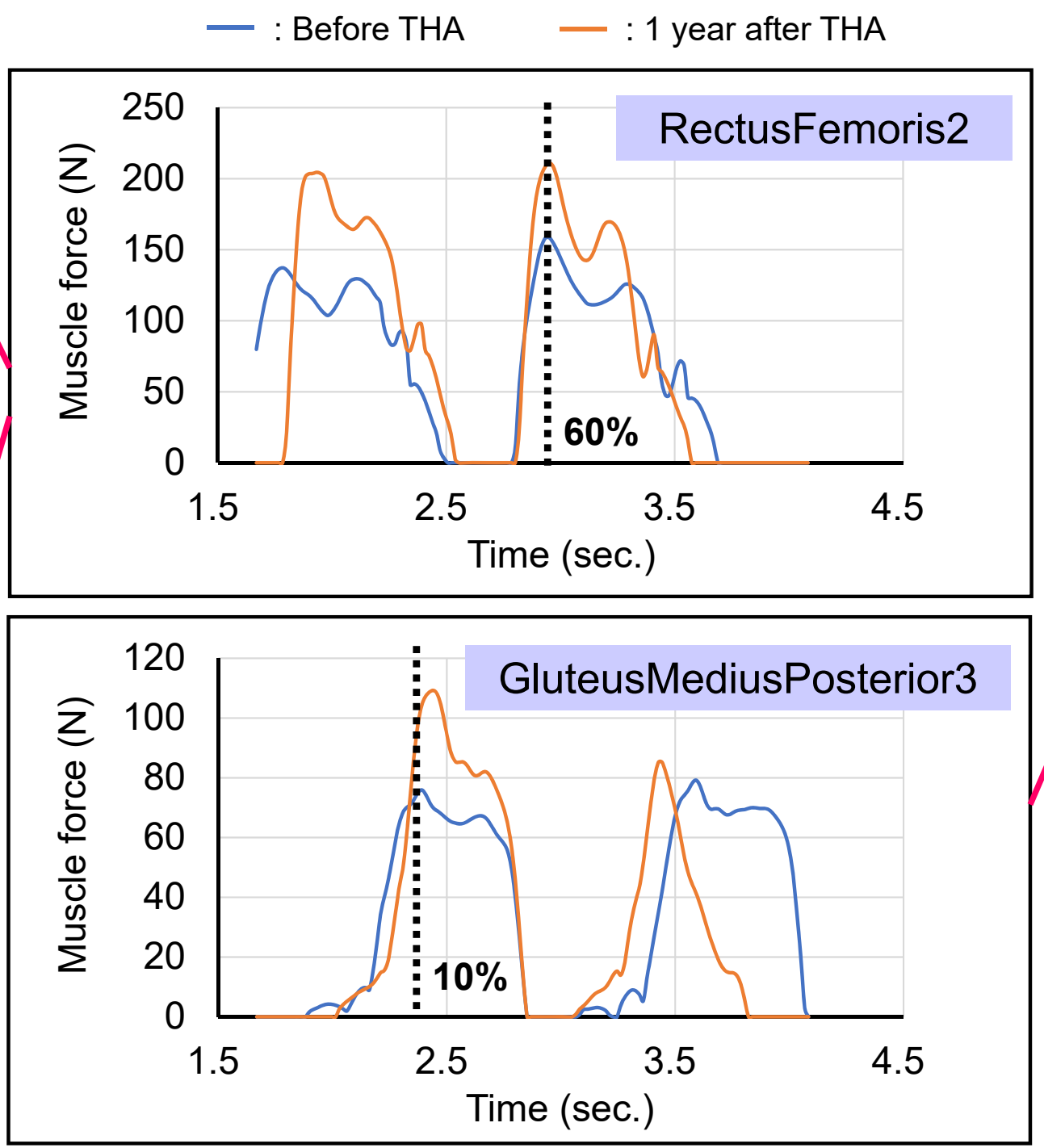


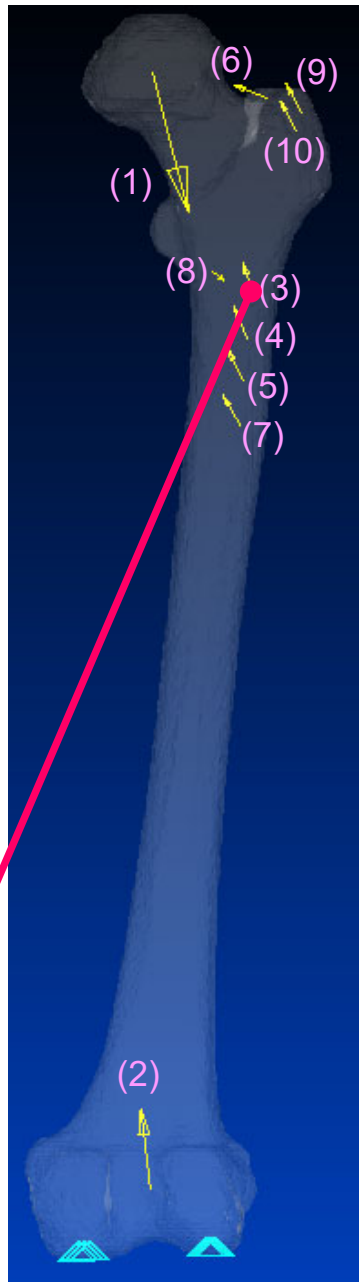


Front Back

Results - Examples of the quantitative comparison of muscles -

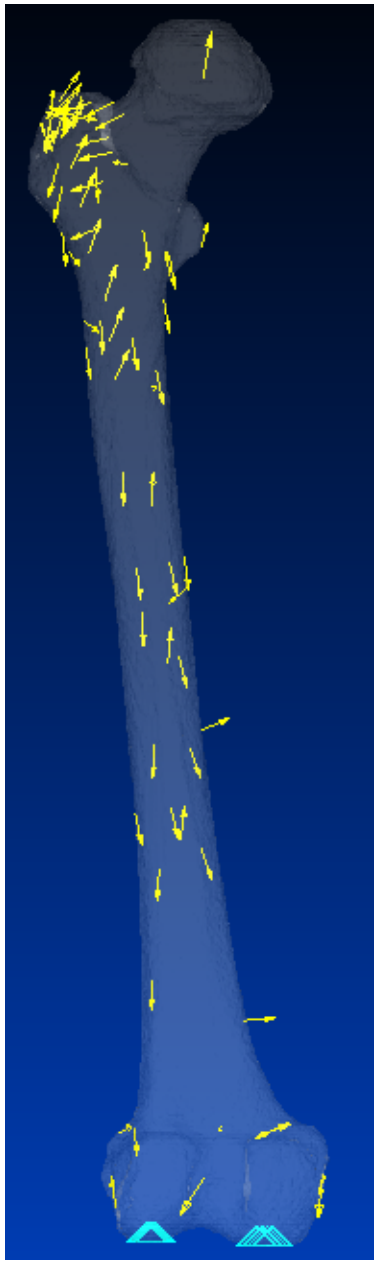
Right femur
(60%)



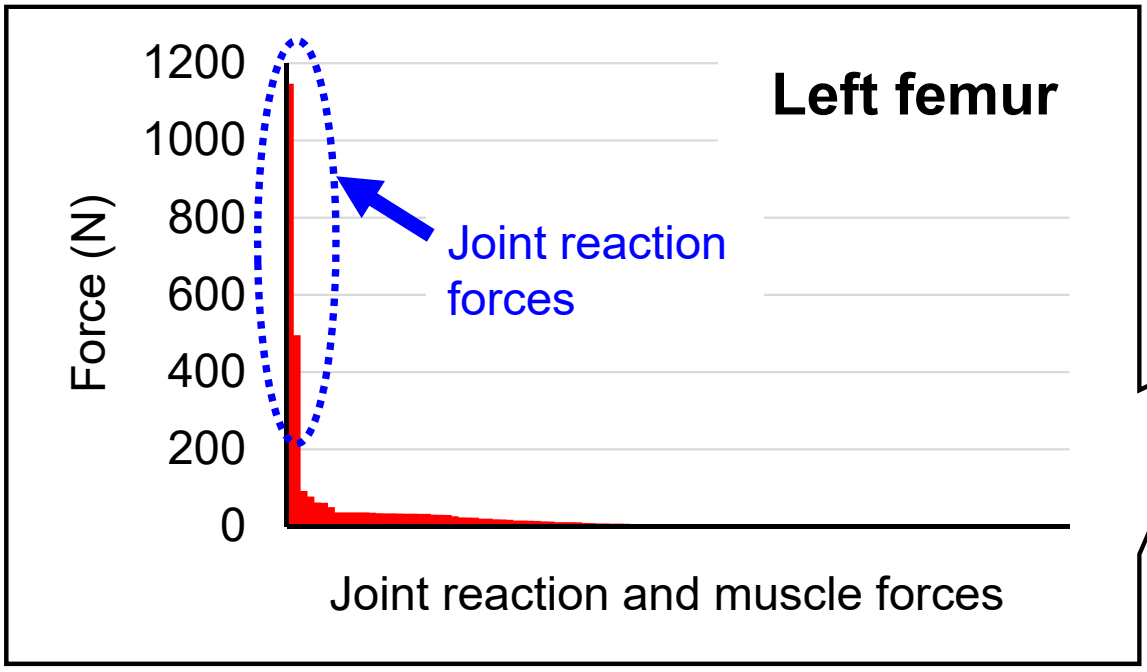


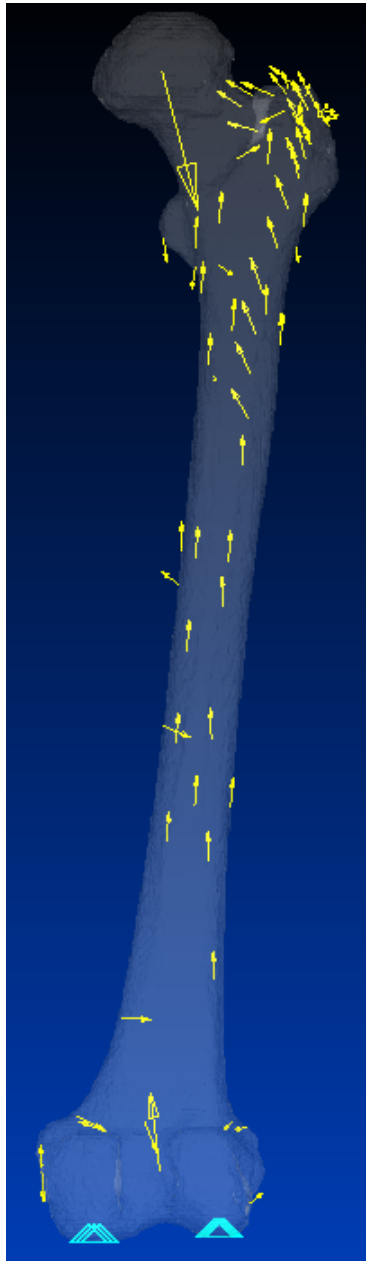
Left femur
(10%)

Results - Display of differences of the BCs in descending order -



Right femur
(All BCs)

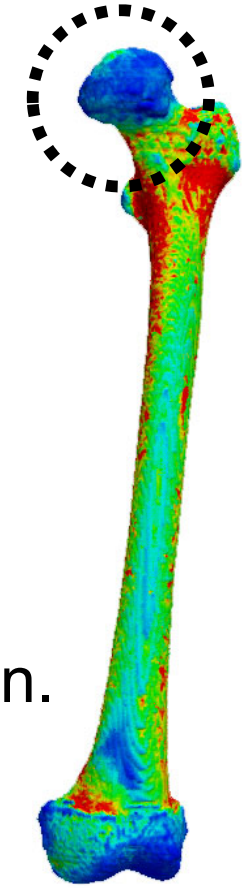




Left femur
(All BCs)

Discussion

- FEA flow still seems to be complicated, but it is the best under the circumstances. Improvement of the FEA flow for a direct link from AMS to MF will be continued.



- The implant inserted in the femur should be modeled, but the approach to assess change in gait posture and stress distribution could be useful to evaluate gait restoration.

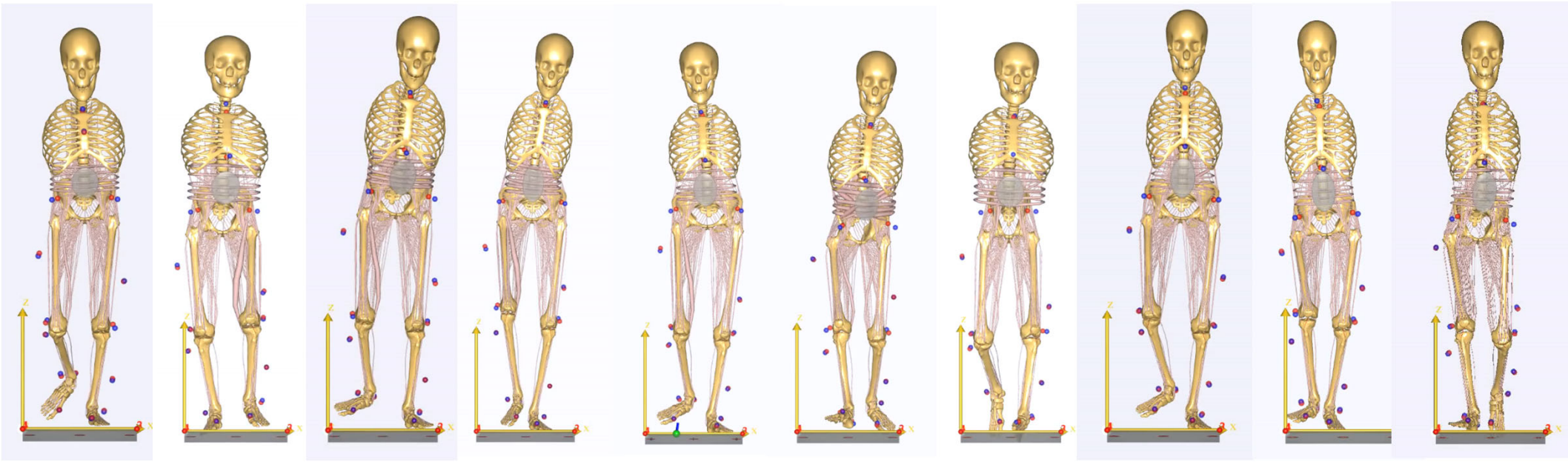
- Display of muscle forces which changed significantly can suggest important muscles to improve gait posture. It can lead to understand the mechanism of abnormal gait and approach of treatment strategy.

Summary

- Basic FEA flow for gait analysis using AMS and MF was constructed and stress analysis of femur under the application of BCs while walking was performed.

- Approach to assess the relationship between change in gait posture and stress distribution can be useful for clinical treatment for abnormal gait of hip osteoarthritis.

Future vision *- Motion capture of patients in progress -*



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Targets

- 50-100 patients
- Gait motion before THA and 1 year after THA

Future plan

- Workflow of musculoskeletal simulation (AnyBody) and FEA (Mechanical Finder)

➡ Statistical prediction

Goals

- Indication to the treatment strategy based on understanding important factors for improvement of abnormal gait
- Prediction of improvement of abnormal gait after THA at the point before THA

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科研費 KAKENHI

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- Research Center of Computational Mechanics, Inc.